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TITLE: Airspace Complexity implementation for an Extended ATC Planner

DEGREE: Grau en Enginyeria d'Aeronavegació

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Resum

Ce rapport décrit l'implémentation d'un serveur de complexité au sein du prototype pré-industriel de l'Extended ATC Planner. Dans un premier temps, nous décrirons la situation actuelle de la salle de contrôle du trafic aérien en-route en présentant les différents acteurs et leurs rôles. La section suivante présente l'étude du multi-sector planner (EAP) dans le nouveau contexte SESAR. Dans la troisième partie, le rapport définit la complexité de l'espace aérien. Il détaille les algorithmes et justifie son utilisation pour l'EAP. Finalement, nous décrirons l'implémentation de la complexité de l'espace aérien dans le prototype de l'EAP. Les architectures de la plateforme et du serveur seront décrites, les simulations et leurs résultats seront analysés et les futures améliorations seront proposées afin de continuer le projet.

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Overview

This report describes the implementation of an airspace complexity server into the pre-industrial prototype of the Extended ATC Planner. First, there is the description of the current ATC en-route control room situation, with a presentation of the different actors and their roles. Then, a study of the multi-sector planner (EAP) is made, focused on the frame of the new SESAR operating method. The third part of the report deals with the airspace complexity. It is defined, then the algorithms are detailed and its applications for the EAP are justified. Finally, there is the description of the airspace complexity implementation in the EAP prototype. The platform and complexity server architectures are presented, simulations and results are analysed and future improvements are proposed in order to continue the project later on.

Remerciements

Je tiens tout d'abord à remercier vivement Christophe Trouilhet et Hervé Damiano pour leur accompagnement durant toute la durée du stage, ce qui a permis de guider mon travail et d'enrichir mes connaissances dans le domaine du développement informatique et l'ATM.

Je remercie aussi Philippe Louyot et Stéphane Degrémont de m'avoir conseillé et dirigé pour ce travail en complexité de l'espace aérien.

Je remercie également Meriem Oubelkass de m'avoir permis d'effectuer ce stage au sein de Sopra-Steria ainsi que l'ensemble du groupe pour leur accueil chaleureux.

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Un grand merci à Mme De Givry pour m'avoir fourni tous les éléments nécessaires pour réussir ce projet au sein de l'ENAC.

Enfin, je souhaite remercier toute l'équipe enseignante de la filière informatique de l'ENAC pour les connaissances qu'ils m'ont transmises pour débuter dans le monde industriel.

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Presentation of the company

0.1 Sopra-Steria

Sopra-Steria is an European leader in digital transformation with 37,000 employees in over 20 countries. It offers to its clients digital transformation and IT services such as: Consulting, Systems Integration, Software Development, Infrastructure Management and Business Process Services. Sopra-Steria aims to enable private and public organisations to make the best use of information technology (IT).

The client who asked for the product developed during this internship is the DSNA's innovation directorate (Direction de la Technique et de l'Innovation, la DTI). The services provided by Sopra-Steria to this client are all kinds of Software engineering services.

0.2 Direction de la Technique et de l'Innovation

The Direction de la Technique et de l'Innovation (DTI) is part of the DSNA, Direction des Services de la Navigation Aérienne, which is also part of the DGAC (Direction Générale de l'Aviation Civile).

DGAC, the french civil aviation authority is responsible of ensuring the safety and security of french air transport, as well as maintaining a balance between development and environmental protection. On one hand it is a regulatory authority, but it also supervises safety, provides air navigation services and training and it is a partner of key players in the aeronautics industry. It is in charge of financial aid for research in aircraft construction and state industrial policy in this sector.

One of its branches is the DSNA, in charge of providing air navigation services in french airspace. This is performed by the operations directorate, which manages 4 CRNA area control centers and has 9 metropolitan airports regional structures.

The second part of the DSNA is the DTI, which is in charge of the study, definition, acquisition, reception, technical verification, deployment and maintenance on operational conditions of the CNS (Communication, Navigation and Surveillance) and ATM (Air Traffic Management) equipments and systems. The scope of this work is not only national but also involved in international cooperation. More specifically, the DTI department where the internship was performed is the "Etudes Europeénnes et Innovation". This part of the DTI is in charge of carrying studies and innovative actions on DSNA systems, placing its activities in an European frame. One of its goals is to make the pre-industrial prototypes of the systems in order to assess and improve the concept developed (through simulations with operational staff). It also works side by side with ATM researchers from ENAC using their studies to inspire or integrate the models. Finally, the project is done in the En-Route cluster, in charge of the activities and tools related to the ATC in en-route at strategic and tactical level.

Introduction

Since the early days of commercial aviation, air traffic has constantly increased. Nowadays, the capacity of European airspace is reaching its limits and air traffic controllers cannot handle more flights. Therefore, it is necessary to find solutions to increase the capacity of the airspace to cope with the forthcoming traffic. In this context the Single European Sky ATM Research (SESAR) project was created. It is a collaborative European project that seeks to coordinate and concentrate all EU research and development activities in ATM. It is the way chosen to develop the new generation of ATM systems that fill the needs in capacity, safety, efficiency and sustainability of European airspace.

SESAR Joint Undertaking (JU) is the European public-private partnership that is managing the development phase of the SESAR programme. It is divided in several Work Packages (WP), each one of them corresponds to a different set of research projects on operational activities, system development activities... The project corresponding to this internship, the P04.07.08, is contained in the *WP4: En-route operations.* Its scope is to provide the operational concept description for the en-route operations and to perform its validation. The 04.07.08 project: Controller Team Organisation, roles and responsibilities in a trajectory based operation within En-route airspace (including multi-sector planner) aims to create a new role in the en-route control room, the Extended ATC Planner (EAP). This new air traffic operational role will handle individual flights for several sectors in a medium time horizon. To perform his duty he will need several tools, one of them is the airspace complexity information of sectors and flights. The airspace complexity is a new metric that tries to measure the difficulty to control a given traffic situation. The main task of the internship is to build and integrate into the EAP prototype a server that provides with this airspace complexity information.

In the first part of the report we will describe the operational en-route Air Traffic Control nowadays. Then, we will see the new role foreseen in the 04.07.08 project: the Extended ATC Planner. Finally, we will study the airspace complexity for the EAP, describe the complexity server architecture, explain the implementation of the server into the prototype and define the future improvements.

Chapter 1

State of the art of the operational en-route Air Traffic Control

1.1 Introduction to en-route air traffic control

The en-route phase is the part of the flight from the end of the take-off and initial climb phase to the beginning of the approach and landing phase (figure 1.1). During this part of the flight, the aircraft is operating at cruise speed and at the flight levels according to its flight plan. In case of air traffic control requirements, the aircraft can be asked to change its flight level, which forces the aircraft to leave its optimum altitude where the fuel consumption is minimized. The purpose of the ATC during the en-route phase is to organize and expedite traffic safely and efficiently. While the primary objective is to prevent collisions between aircraft, controllers shall act by minimizing the impact on the aircraft planned intentions.

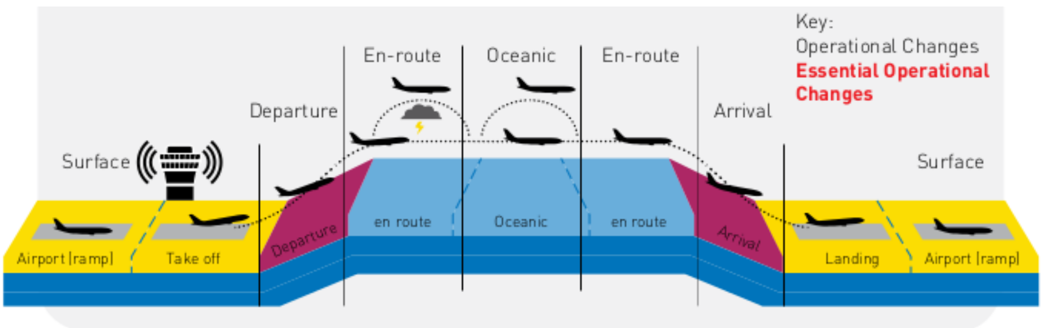


FIGURE 1.1: Scheme of the different phases of flight

The Air Traffic Control (ATC) is the domain in Air Traffic Management that provides traffic control services to aircraft in controlled airspace. Then, there is the Air Traffic Flow and Capacity Management (ATFCM), that regulates the air traffic demand in order to not exceed the capacity of the airspace and airports. Finally, the Airspace Management (ASM) defines the dimensions and classes of controlled airspace. All of them work in a different time window regarding the day of operations, 1 year to 6 days before D-day for ASM, 6 days to 1 day for ATFCM and the day of operation for ATC.

1.1.1 Operational Control room composition

In order to provide air traffic control services to the en-route aircraft there are regional control centers, also called Area Control Centers (ACC). In France there are five of them, called "Centres en-Route de la Navigation Aérienne" (CRNA). Each of them is responsible for a volume of airspace in the french airspace. In order to deliver the ATC services safely and efficiently, the staff of the ACC is composed of different actors working together. Nowadays, the room composition is the following ([figure 1.2), with n pairs of controllers depending on the sector configuration:

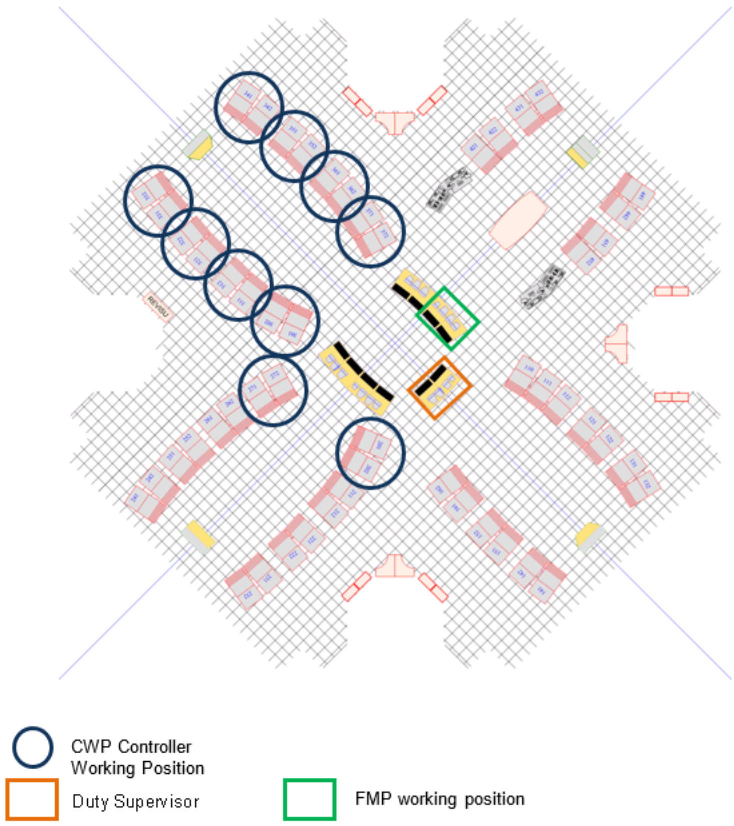


FIGURE 1.2: Control room composition

- A Duty Supervisor

  The supervisor is responsible for all the activities in the Control Room.

- A Deputy Supervisor in charge of the Flow Management Position (FMP)

The FMP provides with the necessary coordination between the ATFCM and the ATC center under his responsibility.

- n Planner controllers

  The Planner Controller (PC) is responsible for providing his own sector team and the next sector teams with conflict free traffic.

- n Tactical controllers

  The Tactical Controller (TC) is responsible for avoiding collision between aircraft and expedite flow traffic.

The following operating methods are based on the French current situation:

1.2 Control Working Position

There are several Control Working Positions (CWP) in a control room of an ACC. Each of them has all the necessary tools for a pair of controllers to handle one sector.

To achieve their duty, a pair of controllers in France has the following tools available for the two working positions:

- A radar visualization screen

  To be aware of the traffic situation at any moment.

- Flight plan data dispatched on paper strips and electronic support as radar labels or flight lists (sorted by exit point or exit flight level).

  To be aware of the aircraft planed route.

- The assistance tool Short-Term Conflict Alert (STCA)

  A ground-based safety net to assist the controller in preventing collision between aircraft generating alerts of separation minima infringements.

- Radio communication with aircraft

  To communicate with the pilots.

- Telephone

  To communicate with the controllers responsible for the adjacent sectors, the FMP, the room supervisor and the technical supervisor.

1.2.1 The Planner controller

The Planner Controller (PC) is responsible for providing his own sector team and the next sector teams with conflict free traffic. For that, he will need to initiate coordination with the relevant adjacent PC.

He is part of the sector team responsible for a designated area. He has to check the planned trajectory of aircraft intending to enter his sector. Then, his principal task is to make sure there are not potential separation risks, and to coordinate entry/exit conditions leading to conflict-free trajectories.

He is responsible for several actions in the following fields:

1.2.1.1 Flight integration

The integration corresponds to the first consultation of flight data, that can be combined with a check of the aircraft position on the radar. At the integration, the controller memorizes flight data, especially route and levels, and also radar position when it is available.

1.2.1.2 Conflict detection

Each controller makes his own conflict detection on the whole traffic of the sector, so there is no hole in the conflict detection and they both have the whole traffic situation in mind.

The planner focuses his detection beyond the boundaries of the sector. He has to:

- Detect conflicts involving every new aircraft (recently integrated).
- Look at the whole traffic, in order to refresh his knowledge of radar positions of aircraft, looking for future conflicts, and check if those new radar positions could generate, or not, new conflicts.
- Look for unexpected conflicts due to last minute changes for example (level, route…)
- Advise the TC of all detected conflicts.

1.2.1.3 Conflict resolution

The planner is responsible for:

- Assisting the TC in the separation task.
- Alleviating the TC conflict resolution workload by negotiating entry and/or exit conditions (FL allocation and/or Heading) that solve the conflict while easing the execution of the exit planned conditions. It is assumed that the planner has a radar assistant role.

1.2.1.4 Complexity management

On a given sector, the Planner monitors the TC workload mainly through the number of incoming aircraft and the number of simultaneous conflicts to manage. Actions to alleviate complexity (sectors splitting, delays on departures. . .) can be initiated by the planner.

1.2.1.5 Other actions

- Traffic monitoring

  The PC monitors the frequency in order to update his situation awareness.

- Communication management

  The PC monitors the frequency to stay aware of the air traffic situation and to the extent possible in order to detect wrongly acknowledged clearances.

- Coordination

  The Planner controller is responsible for all negotiations of flight data changes with adjacent sectors.

1.2.2 The Tactical controller

The Tactical Controller (TC) is responsible for avoiding collision between aircraft. He has to keep separation minima's between aircraft within his area of responsibility, and to expedite flow of traffic.

Additionally, he monitors the trajectory (4D and 3D) of aircraft with regards to the clearance they have received. He is assisted in these tasks by automated tools for conflict detection and resolution, trajectory monitoring and Area Proximity Warning (APW). The responsibilities of the also called Executive Controller are focused on the traffic situation and are very much related to conflict resolution and traffic optimization.

He is responsible for several actions in the following fields:

1.2.2.1 Flight integration

The integration corresponds to the first consultation of flight data, that can be combined with a check of the aircraft position on the radar. At the integration, the controller (PC or TC) memorizes flight data, especially route and levels, and also radar position when it is available.

The TC pays more attention to aircraft with conflict tags from his planner, and looks directly at the other aircraft of the conflict in order to get knowledge of it.

1.2.2.2 Conflict detection

Each controller makes his own conflict detection on the whole traffic, so there is no hole in the conflict detection and they both have the whole traffic situation in mind.

The TC focuses his detection on aircraft within the sector boundaries:

- Taking into account the initial detection made by the PC.
- Looking for conflict involving aircraft he has just integrated (analyze especially based on radar information).
- Looking for new conflicts by consulting regularly aircraft radar positions within the sector.
- Detecting any additional conflict which could be the consequence of any modification of any flight trajectory.

Note that when preparing in his mind a conflict resolution, a controller looks for conflicts that could be generated by the resolution he would like to initiate.

1.2.2.3 Conflict resolution

The TC is responsible for solving all conflicts within his sector.

1.2.2.4 Complexity management

The TC makes his Planner aware of any overload, so the planner takes quickly adequate measures in order to manage this overload.

1.2.2.5 Other actions

- Traffic monitoring

  The TC has to ensure that the flight crew follows the issued clearances.

- Communication management

  The TC gives clearances to pilots through R/T communication, in order to operate conflict resolution or to monitor aircraft behaviour.

- Coordination

  Usually the TC is not involved in coordination with other sectors but with pilots.

1.3 Flow Management Position

The FMP provides the necessary coordination between the ATFCM and the ATC. He is the one having a global view of the control room situation. He deals with traffic flows 3 hours in advance to adjust the expected demand to the capacity.

He is responsible for several actions in the following fields:

1.3.1 Medium Term Planning

These activities are performed in a period from 18 months to 6 days before the day of operations. They consist in identifying predictable problems and to prepare adequate ATFCM measures to manage them. Those problems are related to flows of traffic, special demand days, sector configuration, airfields...

1.3.2 Short Term Planning

From six to one day ahead of time, the FMP prepares the initial ATFCM plan for the day of operation (D day), especially, the FMP determines sectors configurations (which sectors to open and when), and applicable capacities on that day.

Other tasks for this phase include:

- Updating the D+1 daily plan for the Area Control Center (ACC).
- Check military activity and start negotiations if necessary to coordinate sectors occupancy.
- Update information to the CFMU Human Machine Interface (CHMI).
- Check if there are regulations needed for the next morning.
- Initiate some local measures that could be taken the next morning.

1.3.3 Execution Phase

On the D day, the FMP staff on duty monitors the measures elaborated at the pre-tactical level. He works closely with the ACC Supervisor and the Network Management Operation Center (NMOC).

With his close monitoring and analysis, he looks for the highest adequacy between capacity and forecast demand. He can improve the capacity by sector re-configuration and Airspace Management (ASM) negotiations. He manages demand via all ATFCM measures described in the ATFCM manuals from Eurocontrol.

During this phase of execution with real time traffic situation, the FMP also adapts and updates ATFCM measures elaborated during pre-tactical phase. He can improve this measures by monitoring traffic counts and by proposing tactical measures in order to improve traffic smoothness.

Complexity is monitored in an ACC by the FMP, as it is the only place having a global view on the overall load. The FMP monitors a TC workload through CHMI data (occupancy counts and flow counts). Actions to alleviate complexity (sectors splitting, delays on departures. . .) can be initiated by the Supervisor under FMP advisory.

1.4 Limitations and perspectives of the control room

The situation explained above is the one used in all five CRNAs in France. The current context of increase in air traffic is pushing the system to its limits. The ACC are not being able to balance their capacity with the demand, forcing them to apply regulations, unwanted by passengers and airspace users. This is why it is necessary to improve the current system to be able to absorb more traffic.

The biggest problem detected on the current situation is the gap between the FMP ant the planner controllers. While the FMP works with traffic flows at a time horizon up to 5 hours, PCs only start paying attention to the individual flights 10 minutes before entering the sector. This implies also that those two actors have very different ways of solving problems. The biggest part of the FMP work is done during the pre-tactical phase several days in advance with mainly ASM measures. During the day of operation he monitors those measures and can also give advise to the Supervisor on other actions to alleviate complexity such as splitting sectors or delaying departures. In general, those tactical measures are not focused on specific flights but are seen from a network point of view. On the other hand, as for the tactical measures, the PC is only able to negotiate entry and exit conditions of flights from the sector in real time.

It can be seen that there is a lack of coordination on tactical measures between the FMP and the PC. This is why it is necessary to develop a new role that will fill this gap with new measures oriented to individual flights in a short-medium time window (15 minutes to 1 hour). The creation of the Extended ATC Planner role with short-term ATFCM measures (STAMs) will respond to this need.

Chapter 2

A new role in the ATC Control room: the Extended ATC Planner

2.1 Previous MSP studies

There has been several European and American studies that have pointed out the necessity of a new role for a more efficient traffic management during the execution phase. The main task of one of those studies, the European Episode 3 program, was to clarify and justify the SESAR concept of the MSP. Here is an extract:

"A gap was detected in the responsibility time-line between the sub-regional manager (SBR) and the planning controller, as well as in the main focus of their responsibilities: while the SBR focuses on traffic flows, the PLC (Planner controller) handles individual Reference Business Trajectories (RBTs). The MSP covers this gap by proposing changes to the individual RBTs with the aim of reducing complexity and minimizing conflicts within the sectors under his responsibility. This decrease in the number of potential conflicts may lead to an increase in the capacity of the sectors.
On the other hand, the MSP cannot be directly involved in the aforementioned executive controller's tasks. As a consequence, an executive controller assistant may be introduced for safety reasons in certain areas if the planning controllers are totally replaced by the MSP."

Extract from chap 5.2.2.1 Roles and Responsibilities (Execution Phase) D2.5-01 - Episode 3 Final Report and Recommendations

Thus, the goal of the EAP project is to validate this hypothesis of the need for a new role, and the benefits it could bring, in terms of capacity and complexity management. This new role would fill the gap between the ATFCM and the ATC [2.1].

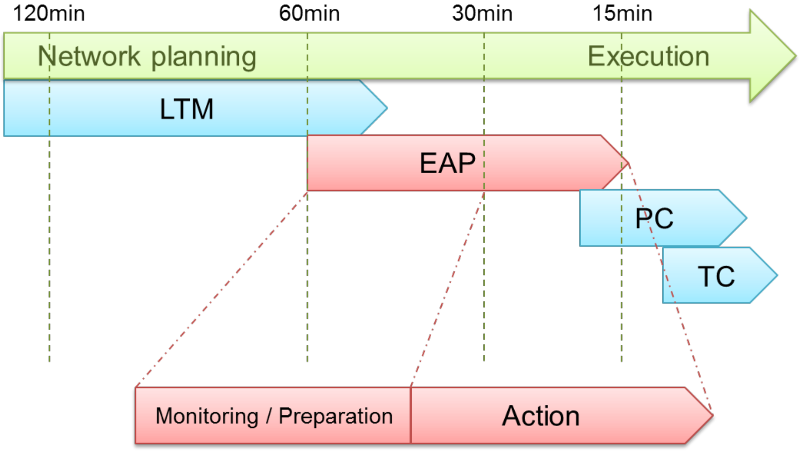


FIGURE 2.1: EAP operational timeline

2.2 Background of the EAP

The EAP concept comes from the Multi Sector Planner (MSP) concept which has been studied for more than 10 years through different programs. The result was the identification of 3 options to implement this new concept:

- A super planner controller replacing some planners from their control working positions (leaving the executive controller alone).
- A Multi Sector Planner acting as a complementary role to the existing Flow Manager Position.
- A planner controller in a free flight environment supported by 4D contracts negotiated via *datalink*.

Out of those three, DSNA decided in 2006 to work on the second option, assuming that this was in the SESAR time frame. In 2013, the Extended ATC Planner emerged from other SESAR projects defining a new role which will fill the gap between the ATFCM and the ATC. The SESAR project 04.07.08 was created to implement the Extended ATC Planner concept and the MSP (as a super planner).

On the other hand, it has been agreed that the first option (super planner controller) will also be developed inside the project 04.07.08. This collaborative control concept will be developed by two European Air Traffic Service Provider (ANSP), the Spanish ENAIRE and the British NATS.

2.3 Timeline of the SESAR project 04.07.08

The timeline of the SESAR project 04.07.08 goes from 2009 to 2016. The project is now in the EAP concept V2, which corresponds to the last part of the execution phase. The EAP concept is now strongly defined, it is starting the final phase of development, experimentation and validation.

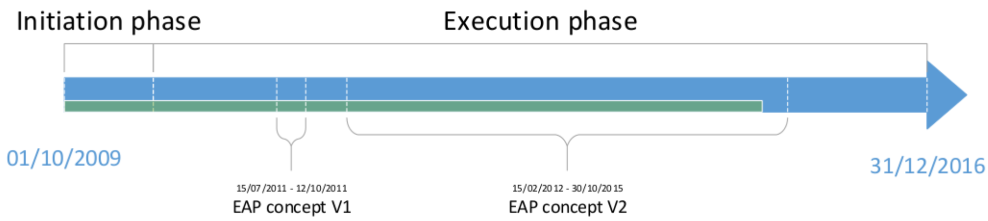


Figure 2.2: Project 04.07.08 schedule

2.4 Detailed new SESAR operating method

The new SESAR operating method of the ACC control room foresees to replace the actual FMP with two new roles: the Local Traffic Manager (LTM) and the Extended ATC Planner (EAP). The LTM will basically inherit the tasks of the FMP while the EAP will perform new specific tasks to continue the action of the LTM and to contribute as well to bridge the gap between tactical Air Traffic Flow and Capacity Management (ATFCM) and Air Traffic Control (ATC). It is important to notice that the EAP position can be insured by a specific EAP specialist but also be collapsed with the LTM in function of the expected traffic. This is why it is important to introduce the LTM first to fully understand the EAP actions.

2.4.1 New SESAR Concepts

The EAP role is part of a wave of innovative measures and concepts driven by the SESAR program. Here are explained the new tools that will be used by the EAP.

2.4.1.1 The dynamic Demand Capacity Balancing

Nowadays, it makes no sense to apply regulations when demand does not significantly exceed available capacity. With the improvements made in capacity monitoring accuracy, dynamic Demand Capacity Balancing (dDCB) helps to switch capacity management from the current global hour-based traffic limitations to minute-based streamlined actions at sector level. This way it is possible to monitor with more accuracy the air traffic controller workload and predict with more refined level of granularity the expected demand. So it will not be necessary to apply big regulations but instead, small ATFCM measures will be enough to adjust demand and capacity by decreasing airspace complexity. This will help improving cost effectiveness, safety, airspace capacity, flight efficiency, flexibility and punctuality.

dDCB follows a process that involves first the detection of demand and capacity imbalance. Then, if the LTM is confident enough with the forecast, he starts the preparation of the ATFCM measures. Those measures are called STAM and are described below.

2.4.1.2 Short-Term ATFCM Measure

Short-Term ATFCM Measures (STAMs) are low impact air traffic measures that are applied by the LTM in coordination with the Network Manager (NM) and the EAP. Their aim is to reduce airspace complexity to not overpass the workload of a controller in its sector. STAMs can be applied to either selected flights or to full traffic flows. Those measures include:

- Flight level capping

  It is done by either delaying a climb or advancing a descent. It is used to protect a high altitude sector that is overloaded. The level capping can be issued on ground or airborne.

- Ground delays

  Consists on delaying the departure of a flight, which is done by issuing a Calculated Take-Off Time (CTOT). Ground delays also include other similar measures like TONB (Take Off Not Before), TONA (Take Off Not After) and MDI (Minimum Departure Interval).

- Horizontal re-routing

  Forces a flight to change his initial route by providing him the new way-points to follow. The horizontal re-routing can be issued on ground or airborne.

- Minimum separation

  Requires that a minimum miles-in-trail separation is maintained between a series of successive aircraft on specific routes.

2.4.1.3 Hotspots

It's a recent ATFCM concept. It corresponds to a high traffic density period of time in a certain traffic volume. Whenever the EAP occupancy curves predict high occupancy values, the EAP can declare a hotspot in that time interval. Then he will propose STAMs to the controllers to alleviate the traffic of the hotspot. It is also useful to warn the CWP that there is a difficult situation coming.

2.4.2 The Local Traffic Manager

The Local Traffic Manager (LTM) is a new role for the new SESAR operating method, developed in the WP 13.02.03 enhanced Demand and Capacity Balancing (DCB) project. It's the updated version of the actual Flow Management Position (FMP). It has new features to incorporate the dDCB measures and to coordinate with the also new EAP role. Therefore, it includes the same tasks than the previously explained FMP. They are explained briefly below, highlighting the new tasks.

2.4.2.1 Description of the LTM

The LTM is involved in dDCB processes both for medium, short term planning and execution phases. He is located between the Flow Manager (FAB level) and the multi-sector planning actors ensuring consistency between the whole ATFCM measures. He is responsible for a group of sectors (potentially a complete ACC).

In case of imbalance, he is responsible for identifying the adequate measures to be taken, in coordination with the appropriate partners, such as the Network Manager, the Flow Manager (FM) or other LTM. To identify those measures he has to understand the operational perception of complexity and translate them into ATFCM requirements. For that he uses traffic load monitoring tools, to compare demand with declared capacity in the Network Operations Plan and to assess sectors workloads and/or complexity compared with predefined thresholds.

2.4.2.2 Tasks of the LTM

The Local Traffic Manager is responsible for:

- Airspace organization and management

  He is involved in ASM measures such as negotiation with military partners to shift or cancel reservation of airspace, alternative sector configuration or use of the flexible division of flight level (vDFL: enables a flexible distribution of traffic between upper and lower sectors by lowering or raising the division flight level).

- Perform, assess and improve ATFCM measures

  He has to perform ATFCM measures such as regulations (CTOT), Short term ATFCM measures (STAM), fine tune and monitor those mesures, assess network effects...

The main differences with the FMP is that the LTM has to be in coordination with the new EAP role. This is necessary for the implementation of STAMs, which are recent types of ATFCM measures. The LTM is also in charge of supervising the EAP to ensure global coherence of all actions taken. Moreover, the LTM and the EAP roles are planned to be performed by the same person in case of low traffic conditions.

2.4.3 The Extended ATC Planner

The EAP role alleviates the LTM workload by working with him on specific flights instead of traffic flows. The EAP acts in its given EAP Area (Multi-sector area of responsibility) which may correspond to an ACC area. In order to be fully efficient, the EAP should be able to appreciate difficulties that a traffic situation could generate from a controller point of view (the EAP works for them) that's why the EAP function should be done by staff having the local ACC radar rating (or had it) and will need an appropriate air situation display dedicated to his/her tasks.

Moreover, it is important to note that any dDCB measure decided will have to remain fully coherent with the Network, this highlighting the need for coordination with the LTM, and the neighbouring ACCs.

The detailed tasks of the EAP are described below:

- The EAP works at the *execution phase* level in cooperation with the LTM function and under the authority of the Supervisor. This real time operational situation includes:

- Acting on flights until approximately 30 minutes before the effective problem to solve.
- Co-monitoring hotspots evolution.
- Elaborating measures to be applied through a CDM process with the LTM.
- Identifying all possible improvements to the traffic situation at ACC level.

- Once an optimized scenario has been decided by the LTM, the EAP selects the individual flights on which to perform the predefined ATFCM or ATC actions and propose them to the relevant sector team planner controller (PC).
- The EAP is responsible for the mitigation of the real time complexity by inter alia managing number of potential conflicts or by allowing counting conflict through a dedicated tool.
- The EAP is responsible for selecting accurate actions through a list of pre-defined scenarios in coordination with the LTM, which will provide better use of actual capacity, by balancing capacity/workload to the benefit of its area of responsibility:
  - Ask for early descent, late descent, or delayed climb to avoid a specific sector in its EAP Area.
  - Balance flight levels to adjust traffic load between layers of airspace.
  - Use of flexible division of flight level, which can be associated with the dynamic FL allocation scheme.
  - Reroute flights:
    - one by one (cherry picking) in case of bunch phenomenon (high density area) to redistribute the traffic to less loaded sectors.
    - to balance the workload between sectors in nominal situations.
    - to take in consideration specific weather conditions.
    - to take in consideration unexpected military activity (or non-activity).

  Some of this actions require coordination with the LTM as they have a network effect beyond the EAP Area (specially when they involve flows of traffic).
- The EAP is responsible of implementing miles in trail procedures. This procedure consists on maintaining an horizontal separation between aircraft that are following each other. This also implies coordination with the LTM, as it has a network effect beyond the EAP Area.
- The EAP has to react immediately to optimize the sector configuration of its given EAP Area when the status of a route or an area changes (military areas, CDR. . .).

- The EAP has the ability to interact with the planning controllers via a communication tool. This tool allows transferring to the sectors the STAM requested by the EAP and getting the answers back. This communication tool will be a tablet computer which allows communicating in an efficient and effortless manner.

2.5 Tools and features of the Extended ATC Planner

The Extended ATC Planner needs a way to access to all the information he needs to get aware of the airspace situation and tools to act in order to perform his duty.

2.5.1 HMI features of the EAP

Here are the Human Machine Interaction (HMI) features state in the requirements document for the EAP. He will have a 4000x2000 screen for the visualization of the information (radar image, diagrams, curves, flight lists...). The interface used during the last operational experiment was the one of figure 2.3.

FIGURE 2.3: EAP HMI used in June 2015

The EAP terminal should display all the following information:

- Occupancy counts

  They indicate the number of flights in the selected traffic volume for every interval of time and in a given time range (up to 2 hours). There will be four main categories of flights: flights airborne, on ground, activated by network services on ground and airborne. The intruders are flights who's flight plan did not stated that there would be in the current traffic volume at that time. The curves shall display the intruders type if demanded by the EAP. A Traffic Volume (TV) is the volume of airspace controlled by a pair of controllers and it is defined by several sectors and many rules to include or exclude flights. For example, if a flight is not geographically in the sector but spends a lot of time very close to the boundaries of it, it can be included in the occupancy curves of the traffic volume.

- Conflict counts

  EAP conflicts count curves should be displayed. An EAP conflict is a conflict calculated on Flight plan data at the entry of a TV. There is also a conflict list of flights available.

- Complexity indicators

  The EAP needs the complexity curves of traffic volumes up to 2 hours. He will also have the complexity associated to flights in a given period of time, for a given traffic volume.

- Flight lists

  The EAP terminal shall allow the display of Flight lists related to a traffic volume, a Hotspot or any complexity indicator for a give time range. This list can be updated on user's demand and the time range can also be modified. There will be access to the following information for any flight:

  - entry time in the considered traffic volume.
  - aircraft information (ID, type, departure and arrival time (actual and estimated))
  - network information (delay, regulation)
  - aircraft flags and indicators: intruders, manually forced, STAM, complexity

  There can also be a list of intruders flights.

- Air Situation Display (ASD)

  The EAP will have a visualization of the air situation that is predicted up to two hours within his area of responsibility. He can visualize flights (and their predicted trajectories), airspace and geographical elements (sectors, military zones, waypoints. . .), conflicts, scheduled STAMs. Shifting to the prediction of the air situation in the future is useful to decide and assess the consequences of the planned actions. The ASD has filtering functions such as the range of FL, airport departure and destination, the traffic volumes, or any published waypoints. Once a parameter is selected, the relevant flights are highlighted.

As for the controllers, each CWP will have a tablet for the management of STAMs. It will allow the coordination, rejection and implementation of STAMs. It will also allow visualizing the proposed, coordinated and rejected STAMs. For each STAM there will be information displayed such as aircraft ID, Hotspot, traffic volume, STAM status, submitted time…

2.5.2 Tools of the EAP

To perform his duty the EAP has the following tools available:

- STAMs Manager HMI

  The EAP is able to create and prepare STAM on a given flight when he is working on solutions for conflicts or hotspots. The interface allows the monitoring, creation, preparation, proposal, edition, coordination, implementation, mutual situation awareness, cancellation, termination and update of STAMs. To provide operational and daily follow-up of the activity he can access to operational history of his STAMs of the day.

  He can also propose, create and prepare requests for a change of level under his area.

- Hotspots

  The EAP can identify and create Hotspots. Due to intruders, manually forced flights and bad predictions regarding taking-off flights sometimes the Hotspots appear very lately in a traffic volume. The EAP will be able to identify the Hotspot and create it.

2.5.3 The Controller Working Position

The controllers on the control working position are the less affected by the new SESAR concept. They will perform the same tasks than before considering only the implementation of STAMs. The planner controller is involved in performing STAMs by ensuring coordination with the EAP. His real time situation awareness and experience allows him to find where and when to apply safely corrections on aircraft trajectories. He will propose the actions to the tactical controller and explain him the benefits. On the other hand, the tactical controller will be in charge of implementing the STAM by giving a clearance to the aircraft involved.

In order to coordinate actions with the EAP, the CWP will have an additional tool, a vertical touch tablet. Placed between the 2 radar screens of the control team, it will allow receiving STAM requests and answering them. For each request, 3 answers are available:

- GREEN: IMPLEMENTED. The STAM request has been implemented.
- BLUE: COORDINATED. The STAM is coordinated between EAP and CWP, in other words, the ATCOs have seen the STAM, analysed it and have planned to do it, the modification being even potentially done.
- RED: REJECTED. It is not possible to implement the requested STAM.

The CWP tool also displays information about the STAM to on-loaded sectors.

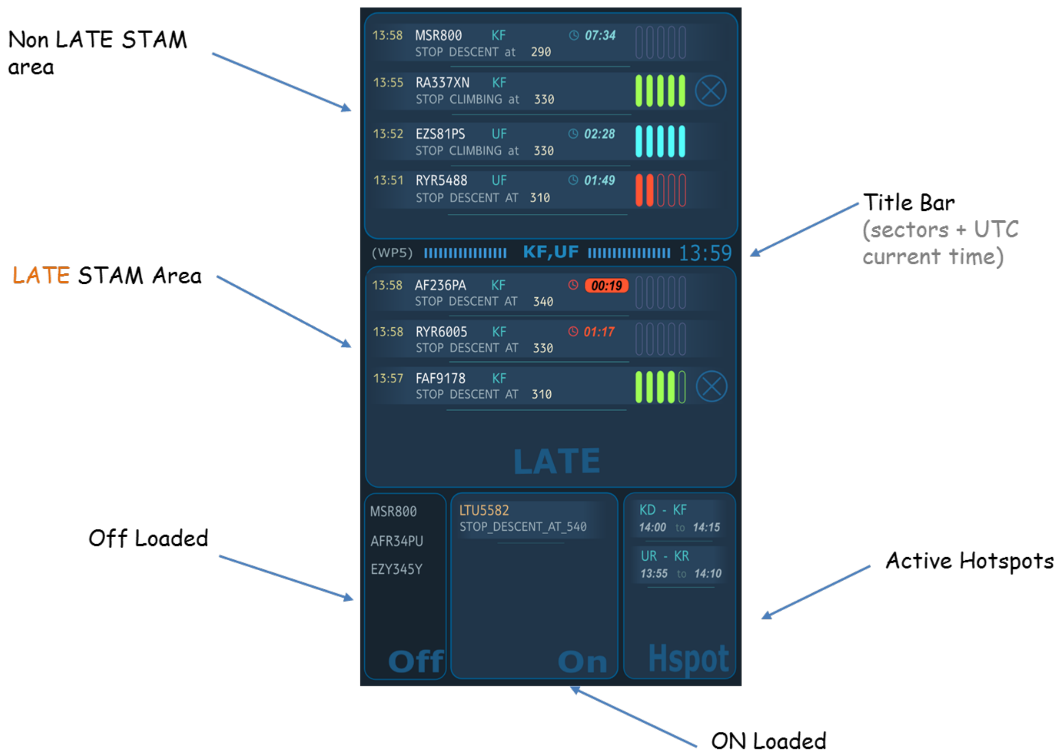


FIGURE 2.4: CWP full tablet view

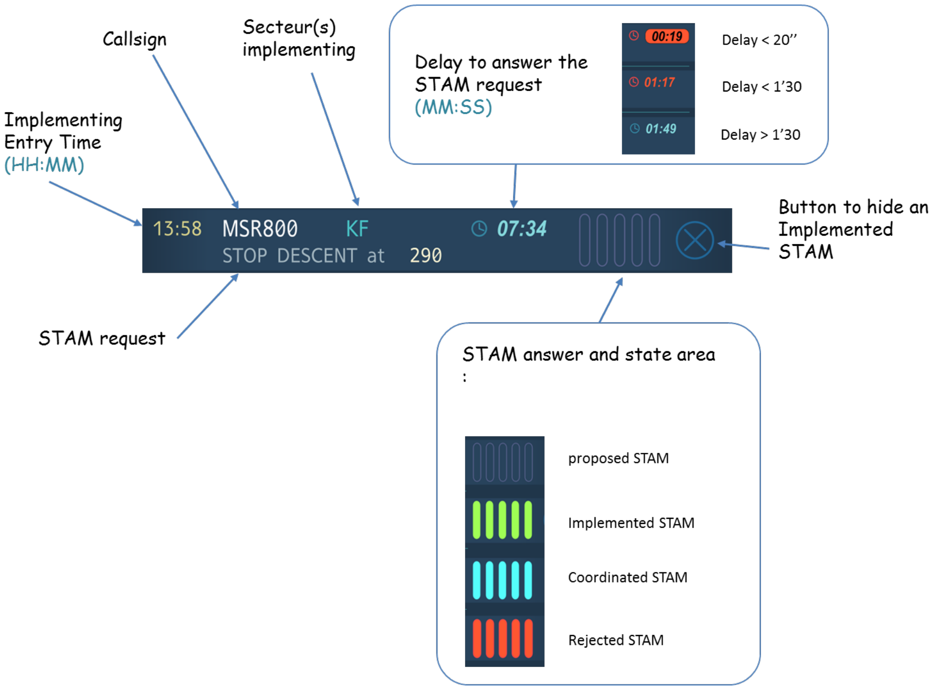


Figure 2.5: CWP STAM view

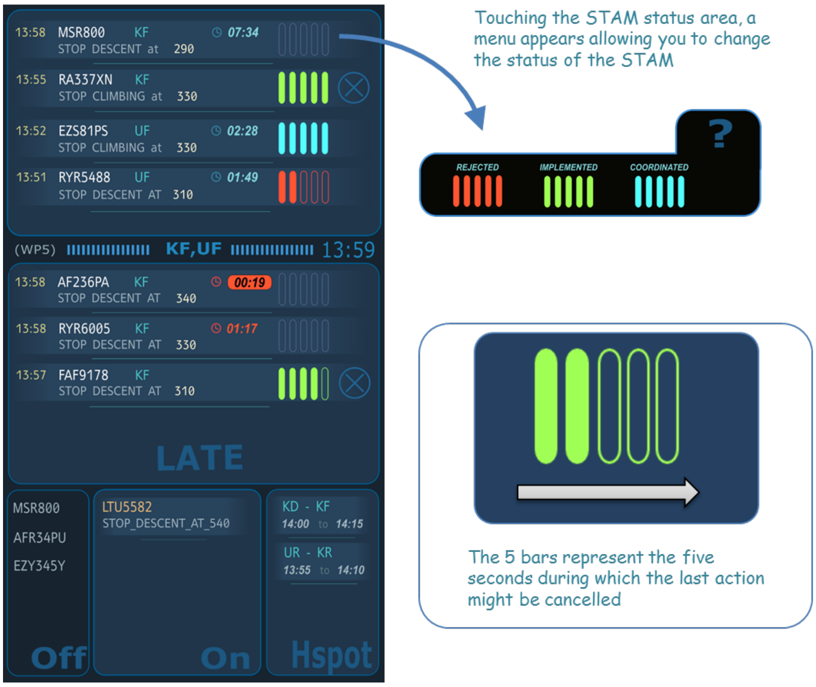


Figure 2.6: CWP full STAM and tablet view

Chapter 3

Study of the Airspace Complexity for the EAP

3.1 Definition of complexity in ATC

First of all, it is necessary to define what do we understand by complexity. Complexity is often associated with a state difficult to analyse or solve. In fact, it is more subtle than that. There is a difference between a complex system and a complicated system. According to Cilliers (1998), if a system consisting of a huge number of parts or elements (and therefore complicated) can be given a complete description, it is not by definition "complex." By this reasoning, a quantum computer or an aircraft are complicated, but not complex. In a complex system, interaction between elements of the system is such that the nature of the whole cannot be determined by analysis of some subset.

Furthermore, in system engineering, the concept of complexity is closely tied to the notion of "entropy" which has been used to describe the state of "disorder" in a system. According to information theory, a complex system is one in which randomness (and therefore uncertainty) is high. This is linked with Air Traffic Control. Controllers have reported that a difficult part of the job is conflict detection, not just conflict solving. Indeed, controllers are very well trained to solve all kinds of conflicts (face to face conflicts, passing, flight level transitions. . .). However, conflict detection is not an easy task, especially when traffic flows are not organized. In a traditional configuration of the airspace, static conflict points appear when two airways intersect or merge. The controller can focus on those points, searching for conflicts. On the other hand, when there is not a clear traffic pattern, conflict detection becomes much more difficult. The system is in disorder, we say then that the situation is complex.

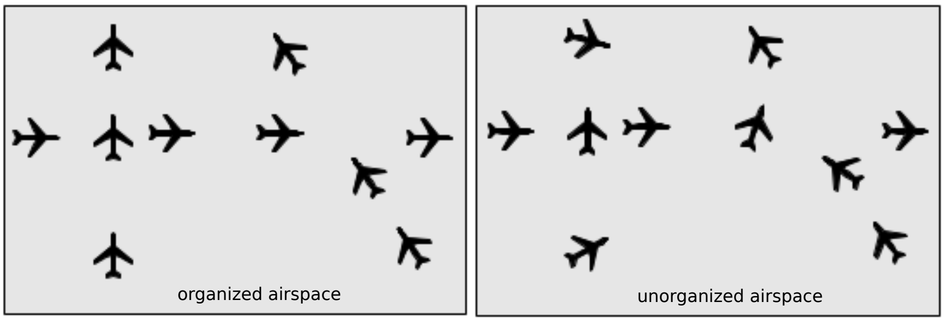


FIGURE 3.1: Traffic flows with structure (left) and without (right). After van Gent et al. (1997).

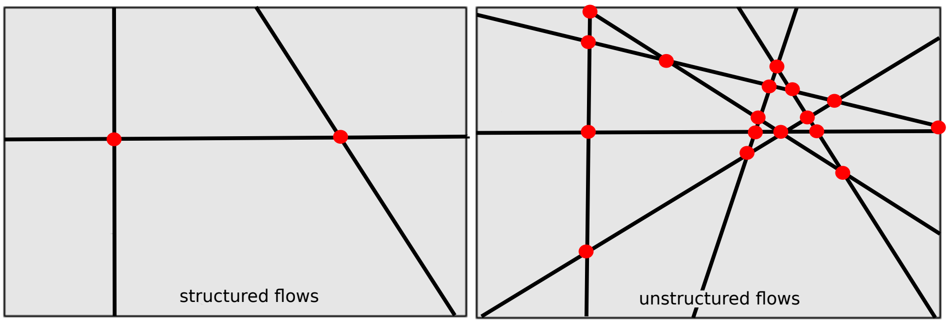


FIGURE 3.2: Traffic flows with structure (left) and without (right).

The figures 3.1 and 3.2 illustrate this phenomenon (we assume that all aircraft are at the same altitude). While in the picture of the left there is clearly a route structure with 3 airways and 2 conflict points, the right one seems totally disordered and there are multiple potential conflict points. The controller will have to pay attention to many points, that grew exponentially with the number of planes in the sector. The task of monitoring and predicting conflicts is obviously harder in the second one.

3.1.1 Relationship between workload and complexity

In an attempt to measure the "level of work" that a controller will face in the performance of his duty, there is the workload concept. Workload in ATC is generally mental, as opposed to physical, in nature. There is a lack of clear definition of what workload is, as it involves intangible cognitive and human factors. First, the distinction is generally made between taskload (the objective demands of a task) and workload (the subjective demand experienced in the performance of a task), as shown in figure 3.3.

The cognitive aspect of workload is not in the scope of this project. It is a field that has been studied for years but remains vague and lacks of appropriate metrics. It poses

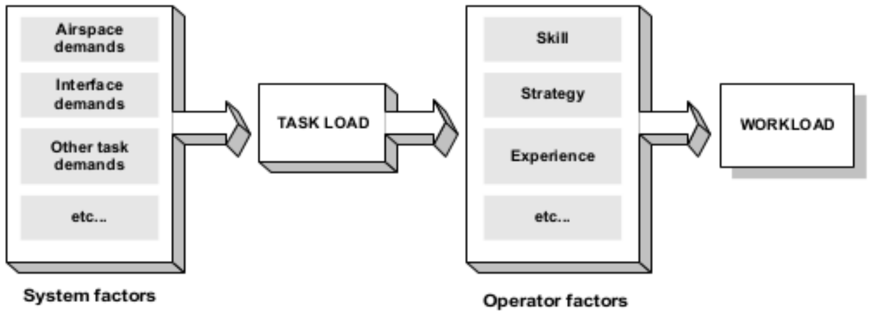


FIGURE 3.3: A model of ATC workload (after Hilburn & Jorna, 2001).

obvious difficulties to fully capturing the notion of cognitive complexity mathematically. However, the second facet of workload, corresponding to the system tasks has been related mainly to airspace complexity. The consensus view among the ATC research and operational communities is that complexity drives controller workload.

Having identify that complexity is a major factor in the computation of workload, lets now analyse what factors affect complexity.

3.1.2 Key complexity factors

No other factor has been more used to compute complexity (and workload) than traffic density. It has been and still is the key factor to measure the capacity of a sector. When traffic regulations are applied, the demand is exceeding the capacity of the sector, which is simply the number of aircraft per sector that the controllers will have to handle during a certain amount of time. Even nowadays, it remains the number one factor to compute controllers workload. However, it is easily provable that the aircraft count inside a sector is not enough to asses capacity. In figure 3.1 we can see that both traffic situations seem really different. In the left one traffic is organized while in the second the traffic is totally disordered. Nevertheless, both situations contain the same number of aircraft, the only difference between the two is that in the right one headings have been altered for four of the ten aircraft. The conclusion is that traffic density is not the only factor that has to be taken into account to asses airspace complexity.

MIT and CENA researchers published [2] a list of key factors influencing cognitive complexity. This list of table 3.1 is based on field observations, ETMS data analysis, and a review of the pertinent literature. Those factors are divided into three categories: *Airspace Factors*, *Traffic Factors* and *Operational Constraints*.

Airspace Factors are those factors related to properties of the airspace. Represented are both internal properties, such as the distribution of navigational aids, and external properties, such as sector shape and coordination activities. In general, these factors are quasi-static, characterizing the underlying context of traffic load.

Traffic Factors are dependent on the instantaneous distribution of traffic. They represent more dynamic and transient effects than Airspace Factors. It is the typical measured factor for complexity.

Operational Constraints are additional operational requirements that place restrictions on possible control actions. These factors tend to represent short-term or temporary variations in operational conditions.

AIRSPACE FACTORS
Sector dimensions *Shape* *Physical size* *Effective "Area of Interest*
Spatial distribution of airways / Navigational aids
Number and position of standard ingress / egress points
Standard flows *Number of* *Orientation relative to sector shape* *Trajectory complexity* *Interactions between flows (crossing points, merges)*
Coordination with other controllers *Point-outs* *Hand-offs*
TRAFFIC FACTORS
Density of aircraft *Clustering* *Sector-wide*
Aircraft encounters *Number of* *Distance between aircraft* *Relative speed between aircraft* *Location of point of closest approach* *(near airspace boundary, merge points etc...)* *Difficulty in identifying* *Sensitivity to controller's actions*
Ranges of aircraft performance *Aircraft types (747, Cessna)* *Pilot abilities*
Number of aircraft in transition *Altitude* *Heading* *Speed*
Sector transit time
OPERATIONAL CONSTRAINTS
Restrictions on available airspace *Presence of convective weather* *Activation of special use airspace* *Aircraft in holding patterns*
Procedural restrictions *Traffic management restrictions (e.g. miles-in-trail requirements)*
Communication limitations

TABLE 3.1: Key complexity factors reported by controllers as influencing cognitive complexity

One of the airspace factors corresponds to the sector "Area of Interest". This area is greater than the dimensions of the sectors. Indeed, aircraft outside of the boundaries of a controller's sector can be important for decisions regarding aircraft currently within the sector. This adds complexity as controllers have to pay close attention to those flights too.

3.2 Airspace complexity studies

There has been many studies on airspace complexity in research laboratories around the world. Nevertheless, very few have been implemented and used in operational scenarios. Some metrics have tried to aggregate complexity factors on a single indicator with a pondered sum. Most recent studies try to obtain complexity out of intrinsic characteristics of the traffic. Those algorithms are the ones used for the complexity server. Lets see two of them, both developed by ENAC researchers Daniel Delahaye and Stéphane Puechmorel.

3.2.1 Convergence method

This approach is based on the properties of the relative positions and the relative speeds of aircraft in a sector. When a set of aircraft is considered in a sector, it is possible to identify different areas for which the structure of traffic is different. For example, it is possible to identify some high density zones and clusters of traffic with strong disorder. This identification is done by our brain which investigates the different structures and is able to recognize structure symmetries. The current approach, proposes some metrics in order to quantify this feeling of disorder and produces a new representation for which each aircraft may be assigned to a point in a complexity coordinate system.

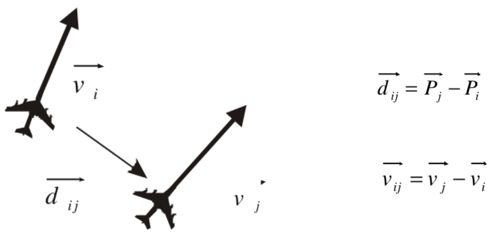


FIGURE 3.4: Relative distance and speed between aircraft

When two aircraft are considered, it is possible to define their relative distance and their relative speed [3.4]. Then, we can apply the following formula [3.5] to compute a metric of convergence. This formula has to be applied to each aircraft. It will assign to an aircraft a complexity value (or convergence value in this case). This value is computed with the relative distance and speed of this aircraft with respect to all the others in the sector (one by one). This can be seen with the sum that goes to N, the number of aircraft in the sector. The formula also shows that when the relative speed of two aircraft is high (first factor) the more complexity we have. Indeed, that situation is more conducive to generate a collision. The second factor, which is the indicator function on R^- of the relative distance, is zero if the relative speed is positive. Indeed, if the relative distance increases (aircraft diverge), the convergence value should be zero. Finally, the exponencial factor is used to increase the convergence value if the relative distance between aircraft is low. It can be adjusted with the two parameters R (neighborhood distance) and α (weighted coefficient.

$$Conv(i) = \sum_{\substack{j=1 \\ j \neq i}}^{N} \left| \frac{d\left\|\dot{d}_{ij}\right\|}{dt} \right| . 1_{R^-}\left\{ \frac{d\left\|\dot{d}_{ij}\right\|}{dt} \right\} . e^{-\alpha \frac{\left\|\dot{d}_{ij}\right\|}{R}}$$

Figure 3.5: Convergence formula for each aircraft

After the computation of convergence we obtain a map with complexity points, that shows the high complexity zones (where aircraft tend to be more in conflict between them) and the less disordered zones.

3.2.2 Lyapunov method

This method definitely refuses to use a single aggregate indicator to compute complexity but instead obtain a measure of intrinsic complexity related to the traffic structure. This computation is done in several steps. It is not necessary to detail the mathematical formulas to understand the general concept of the algorithm.

First, it is necessary to obtain the underlying dynamical system (vector field) based on the speed vectors and positions of the several aircraft in the sector (figure 3.6). It is done with a dynamical regression based on radar observations. The vector field gives a general view of the traffic pattern in the sector. Then, to compute the complexity metric, Lyapunov exponents are used. This metric relies on a measure of sensitivity to initial conditions of the vector field (figure 3.6). To understand this, let's consider a point (x_0) and look at its evolution when transported by the dynamical system. The trajectory it will follow according to the vector field is $\gamma(t, x_0)$. However, if we apply a small perturbation to its initial position (x), the trajectory becomes $\gamma(t, x)$. The distance between the two trajectories is $D(t, \gamma)$. The more this distance is high and increases with time, the more the Lyapunov exponents are high.

So, when Lyapunov exponents are high, the trajectory of a point under the action of the dynamical system is very sensitive to initial conditions (or to the parameters on which

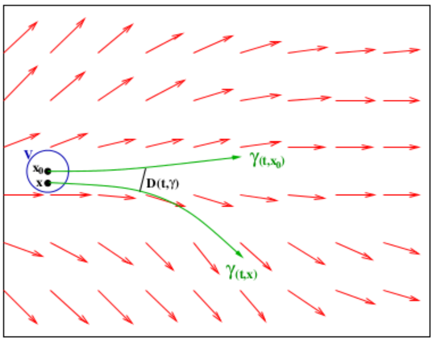


FIGURE 3.6: Time evolution of a reference trajectory ($\gamma(t, x_0)$) and a perturbed trajectory ($\gamma(t, x)$)

the vector field may depend), therefore, situation in the future is unpredictable. On the other hand, small values of the Lyapunov exponents mean that the future is highly predictable (expected to be comfortable for a controller). Then, it can be said that the Lyapunov exponent map determines the area where the traffic is organized and where it is not. This is a critical point to identify airspace complexity. The less organized the traffic is, the more difficult is to detect conflicts for the controller, thus, the more complex the situation is.

3.3 Airspace complexity for the EAP

Having explained two airspace complexity metrics, lets see what are the requirements in terms of airspace complexity for the Extended ATC Planner. As explained before, the airspace complexity can measure the level of disorder of the traffic (difficulty to detect conflicts), therefore, controllers difficulty to manage traffic. Thus, airspace complexity is an *indicator* that can be useful for the EAP to predict high workload situations. Furthermore, we have seen that complexity metrics can also detect specific zones of disorder and associate complexity to flights. This could be used to draw a rank of flights with higher complexity values. This would help to decide to which flights it is better to apply STAMs. In that case, the complexity information would be used as a *solving* tool.

The airspace complexity requirements for the EAP are:

- Complexity curves for every Traffic Volume

  In order to predict complex traffic situations, it would be useful for the EAP to have a complexity curve for every traffic volume (in addition to the occupancy curve). We have seen [3.1.2] that the occupancy curve is not enough to determine the controller's workload. With the complexity information, the controller will have complementary information. To get those curves, the computation will be the *sum* of the complexity values associated to each trajectory in the TV in function of time (up to 2 hours). There has to be a value every minute. The complexity sum is useful to get an idea of the amount of complexity in the TV but does not give information about the number of aircraft in it. This information can be obtained with the occupancy curve. The complexity mean (mean value of complexity of every aircraft in the TV) could also be a useful value but it has not been assessed yet.

- Complexity value for each aircraft in a TV

  When the EAP will select an interval of time in a traffic volume, he will obtain the list of flights that are in the TV during this interval. Each flight will have a list of data. One of the sections will be a complexity value. This value will be computed as the sum of the complexity points predicted on this trajectory in the considered TV. If the time interval corresponds to a hotspot and the EAP wants to apply a regulation on one or several flights, he can be guided by this value picking the ones with higher complexity. Again, the value computed is a sum, it is not known yet if the value should be a sum or a mean.

It is important to note that the project corresponds to a research and development project, where the requirements are updated after simulations following a process similar to the Agile software development. This iterative process is based on continuous feedback to successively refine and deliver the software system. The complexity part of the project is on its first steps so there are not specific, contrasted and clearly defined requirements. Hence, it is not yet known if the complexity value needs to be the sum of the flight's values, the mean or some other computation. The same goes for the display of the information (curves, maximum values, merged graphs with conflict counts…). Those uncertainties will be redefined after the first simulations with the client's feedback.

In addition, it is still to early to say that airspace complexity can be used as a solving tool. To decrease a complex situation, the flight with higher complexity value is not necessarily the best option to remove. As we have said, the complexity algorithm computes the complexity of an aircraft with respect to the others. It cannot be said that an aircraft is by itself complex as it depends on the other aircraft. Furthermore, there is differences between the two algorithms in terms of the meaning of the complexity values. For the Lyapunov algorithm, when a flight has high complexity, it represents that the flight is in a disordered zone but does not mean that the flight is by itself complex and that therefore that is the one that should be removed.

Chapter 4

Airspace Complexity implementation in the EAP prototype

Having explained the airspace complexity requirements for the EAP, this last part describes their implementation in the EAP prototype.

4.1 Description of the EAP platform

4.1.1 EAP platform

The Project 4.7.8 ”Extended ATC Planner” system’s platform consists of several servers that communicate through a communication bus [4.1]. All those servers send and receive data through the bus to perform their computations. The communication bus is a DTI/EEI (ex CENA) product called Ivy. Ivy is a simple protocol and a set of open-source (LGPL) libraries and programs that allows applications to broadcast information through text messages, with a subscription mechanism based on regular expressions. The main characteristic of this bus is that an object can be ”observed” by other objects called observers and notify them automatically of any state changes. In this prototype, this means that a server will have other servers (in client mode) that will get notify whenever the server has new computed data available and ask for it. As an example, when the traffic info server receives the flight plans from the NMOC (Eurocontrol), he notifies all its observers and sends this information. Clients such as the CHMI, the ASD or the occupancy server will want to get this information and pick it from the bus. The data is stored in each server using observable collections. Those collections are specific to each type of data and are instantiate as objects in each server.

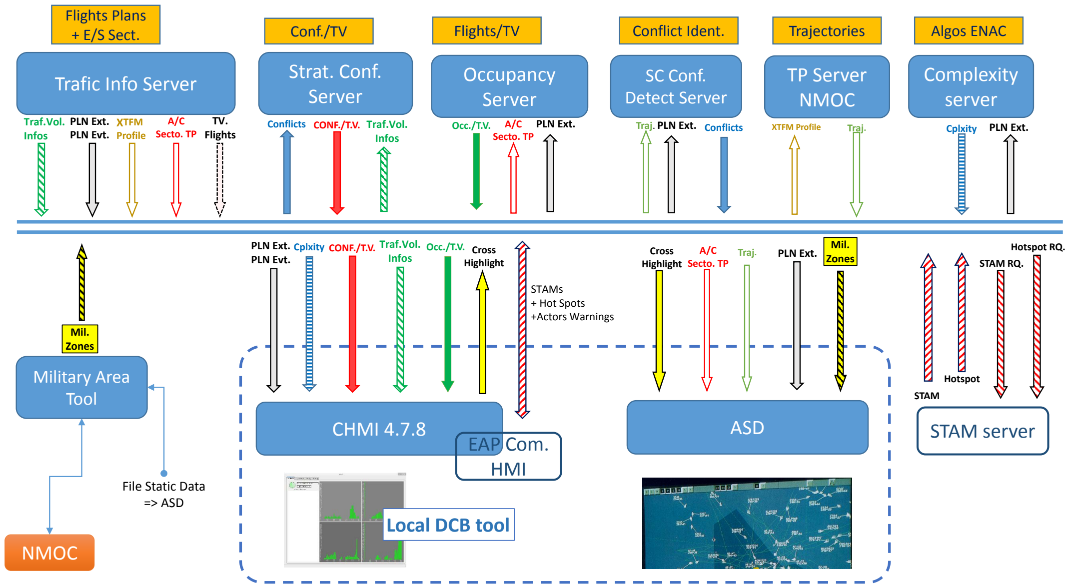


FIGURE 4.1: EAP platform structure, including the bus, the servers and their required data.

4.1.2 EAP platform simulations

To simulate a traffic situation and test the system there is two different approaches. The first one is to obtain the traffic from a data file. This data was taken from a real traffic situation once and is being replayed when needed. The benefit of this method is that the same traffic is simulated every time, allowing to compare the results of every simulation. This is useful to see how variations on initial parameters affect the results. Then, the second approach is to get the live traffic from Eurocontrol. The traffic server will launch requests every 5 minutes to the Network Manager Operations Center (NMOC) server in Maastricht. The NMOC delivers ATFCM services to the whole Europe network. The received trajectories correspond to live operations. This method is essential to test the server in live conditions to get more and more cases.

4.2 Description of the complexity server

The complexity server is in charge of computing the airspace complexity data for the EAP. This server did not exist at the beginning of the internship. I have designed and implemented the complexity server. I was assisted by Mr. Louyot who was in contact with ENAC researcher Mr. Delahaye to obtain and integrate the complexity algorithms into the server.

4.2.1 Server interface

As explained before, each server of the EAP platform sends and receives data. The following diagram [4.2] shows the different agents that interact with the complexity server. Let's see more in detail the inputs and outputs of the server.

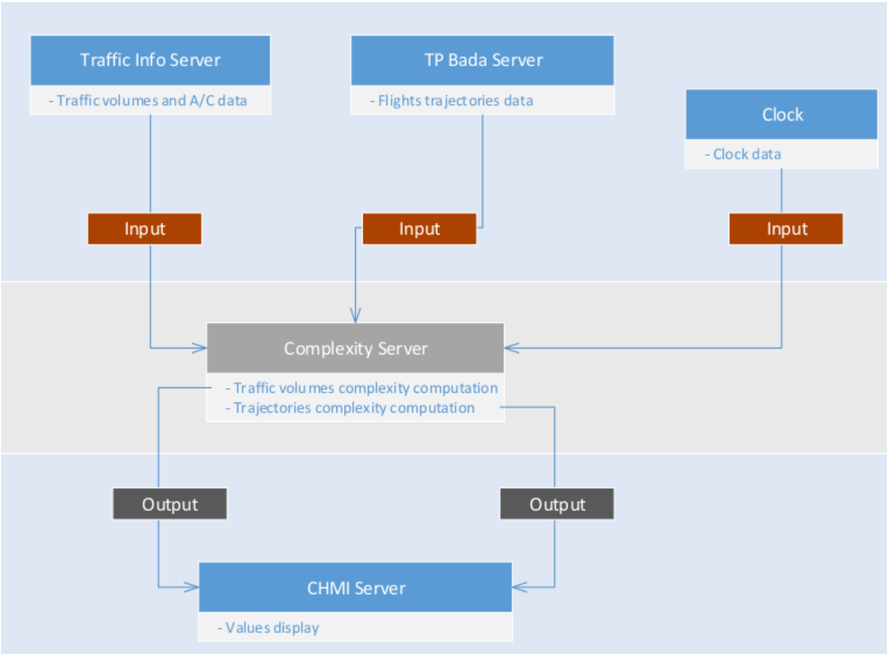


FIGURE 4.2: Server's interface diagram

4.2.1.1 Inputs

The server gets from the bus 3 types of information:

- Flight trajectories

  The server needs flight trajectories to feed the complexity algorithm. Those trajectories are delivered to the bus by the Trajectory Predictor (TP) server that computes them out of flight plans. Those predicted trajectories are made of 4D points.

- Aircraft sector prediction

  It is not only necessary to compute the complexity of the trajectories but we also want complexity information for every traffic volume. Which sector the aircraft is in at any time, is an information given by the A/C SectorTP. It is used to divide the trajectories in sectors, and hence, obtain the complexity for every TV.

- Clock time

  Even if it is not mentioned in the figure, all the servers need the current clock time (live or simulated). For the complexity server, it is used to predict the complexity from the current time (live or simulated).

4.2.1.2 Outputs

The server sends through the bus 2 types of information. Both will be collected by the CHMI to display this information.

- Complexity for each Traffic Volume

  The complexity data is divided per traffic volumes. In fact, the complexity is also divided per time (called offset). For every TV at any minute of the time window presented to the EAP there will be a list of the flights contained in the TV with a complexity value. Storing all the flights contained in the traffic volume (its Cautra Id and complexity value) at that time instead of a simple complexity number is useful. Indeed, it is not yet defined the mathematical operation to be applied to the values (sum, mean...). This way it gives freedom to the CHMI to compute any value.

TV	Offset (min)	<Id cautra;Complexity>
		<Id cautra;Complexity>
		<Id cautra;Complexity>
		<Id cautra;Complexity>
		:
		:

LFE2F4	62	<113;15,3>
		<142;18,2>
		<205;6,6>
		<453;22,8>
		:
		:

FIGURE 4.3: Example of storage for the complexity per TV database

- Complexity for each trajectory in each Traffic Volume

  This category is needed to obtain the complexity of flights when the EAP is selecting a traffic volume. As for the previous output, this data will be stored keeping all the complexity values of the trajectory inside the TV. Hence, each flight having a part of its trajectory inside a TV is stored. The result in the database is a list of complexity points (including time and complexity value) for a specific flight in a specific TV.

Another very important output that will not pass through the bus is the trace data. This data is used to monitor the activity of the server during a run. It will be collected

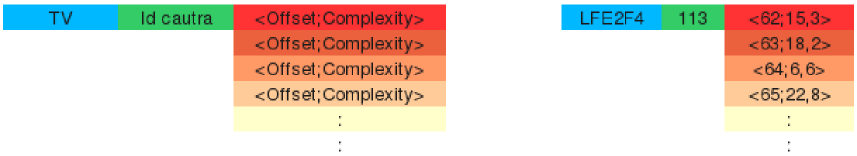


FIGURE 4.4: Example of storage for the trajectory complexity per TV database

periodically during the run and processed afterwards. This data is essential to assess the benefits of the server and validate results. In order to evaluate the benefits of the complexity forecast, this output will allow to draw curves of error between the expected complexity (up to two hours) and the real complexity (measured at the current time).

- Trace data

  The data stored every x minutes during a run (usually 20 minutes) is the complexity forecast every delta time interval for a fixed time window. A typical example would be to store every 20 minutes the current complexity, the one expected in 20 minutes, in 40 minutes... until 2 hours in advance. With this data it is possible to compare the expected values with the final real values and obtain the errors. This task is also performed by the server at the end of the run. This allows obtaining for every time interval (20 min, 40 min...) a curve of forecast error. This will allow to assess the truthfulness of the prediction and therefore, its utility.

In order to prevent the possible loss of data in case of a program crash the data is stored in a new file every delta time. Then, at the end of the run, all the files are merged in a single one. This way there are not opened files during the run, all of them are closed after writing process is finished.

4.2.2 Server architecture

The following diagram [4.5] shows the subsystems and their interactions. It can be seen that there are three inputs. One of them comes from an observable collection, initialized in the complexity server, which is fed periodically by the Traffic Info Server and the TP Bada Server. This collection contains the TV and trajectories information. The data of this collection is periodically updated with new trajectory predictions. The second input is the clock data, which is necessary to synchronize the server with the current time (live or simulated). Finally, the third possible input is the complexity requests. The server can receive complexity request at any time from other clients that would want to obtain the complexity data immediately.

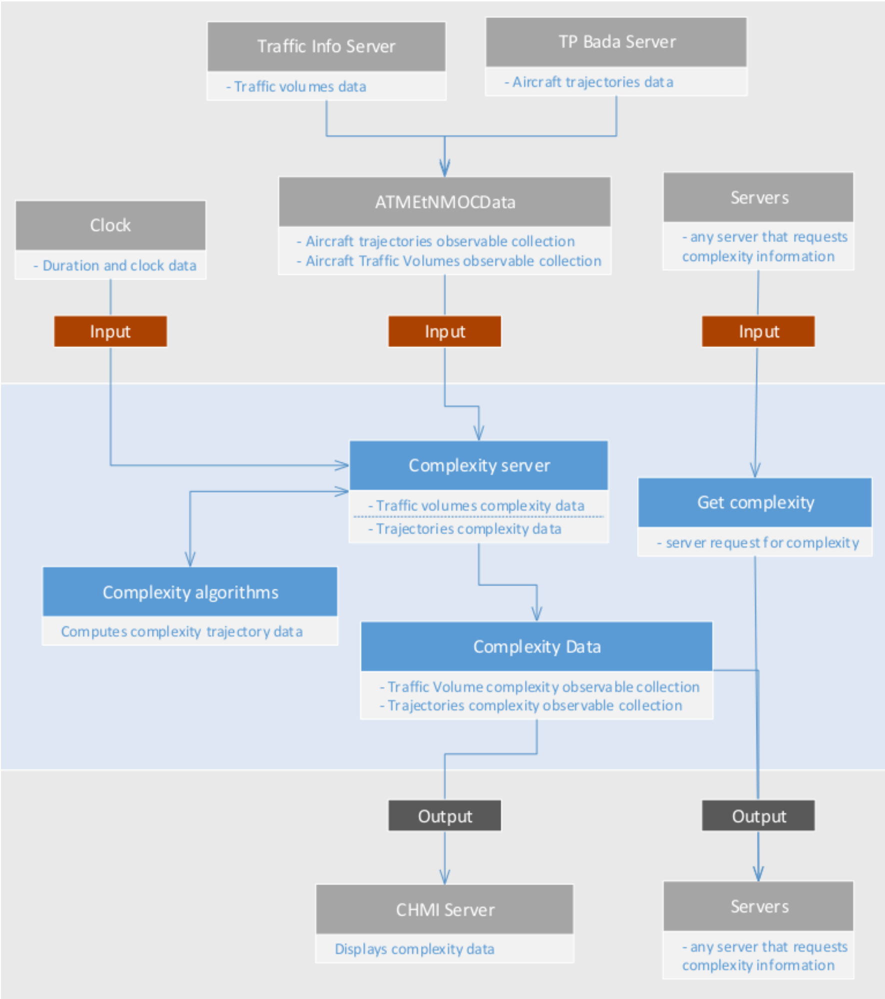


FIGURE 4.5: Server's design diagram

Inside the server, the 4D trajectories points are enriched with complexity values from the complexity algorithms. After that, those trajectories plus the traffic volumes are fed to the module in charge of computing the complexity data per traffic volume and trajectories. This resulting data is stored in an observable collection, specifically designed to store complexity data. This collection, initialized in server mode inside the server will send periodically its data through the bus. The CHMI server will have its own collection, in client mode, which will collect the data circulating through the bus. Finally, it will display the information.

4.3 Simulation examples and results

In order to validate the complexity results it is necessary to do some simulations. The dataset used for the simulations is the REIMS control center one. The traffic used is the one overflying the REIMS ACC upper airspace [4.6].

FIGURE 4.6: REIMS ACC airspace, used for the simulations

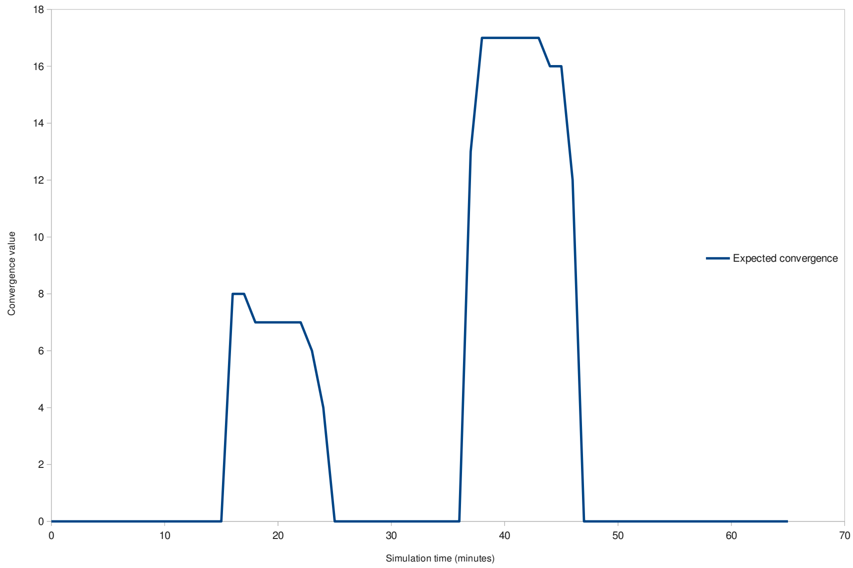
The traffic used to perform the simulations comes form a file. The first test is done with only a single conflict to see clearly how the algorithm performs. All the following test are done with the **Convergence** algorithm, which is the one installed at the moment.

4.3.1 Single conflicts

First, let's see how the algorithm behaves when there is a simple conflict between two aircraft. For that, a simulation has been done with only three aircraft, all flying at the same flight level. The flight AZA135 will be in conflict with the IBE4535 and 10 minutes later with the RYR5625. The results are shown in figure 4.7.

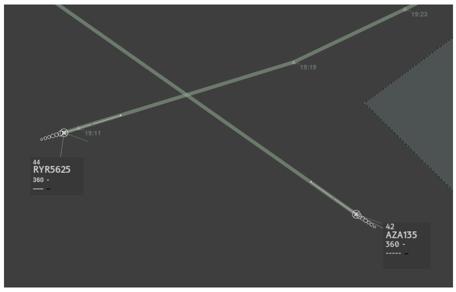
There are several concerns about the operation of the convergence algorithm. First, the two conflicts are clearly visible in the complexity curve. When there is a conflict, the shape of the curve is similar to a pulse. The first conflict corresponds to the first pulse, that goes from the 15 minute of the simulation to the 25 minute, and the second conflict goes from the 36 minute to the 47 minute. Both pulses are not the same height, The first one has approximately 8 points of complexity while the second one has around 17. This is because the convergence algorithm measures the speed variation of the distance between the two aircraft. In the first case the aircraft trajectories have an angle of 35° while in the second they are close to a face to face (130° aprox.). They are getting closer faster which is considered as a more complex situation, so there is twice the convergence value.

It can also be noticed that both pulses are not perfectly flat at the top. This is because the aircraft headings are not constant because they depend on the trajectory prediction.



(A) Convergence curve for 2 aircraft conflicts

(B) Radar image of the first conflict



(C) Radar image of the second conflict

FIGURE 4.7: Convergence curve for 2 aircraft conflicts

This causes small changes in the aircraft relative speed and therefore the complexity value varies.

The fact that the top is flat means that the algorithm doesn't take into account the relative distance between the aircraft. When the two aircraft are getting closer to each other this leads to a more critical situation. It would be more realistic to include this phenomenon in the algorithm by having an increasing curve instead of a flat one.

Other concerns are for example that the algorithm doesn't consider necessary to have complexity when aircraft are not flying at the same flight level. This could be modified if we want to increase the perception of disorder that the controller will have. Even if there will be no conflicts, the situation can look complex, maybe it could be needed to represent that in the curve. The duration of a conflict could be modified also by changing the distance before collision when complexity starts.

Finally, it can be notice that the convergence axis doesn't have units. Indeed, it would not be logical to put them as it is a new metric that varies in function of the algorithm used. In addition, a multiplier has been added at the output of the algorithm to have integers values, which are more visual and easy to understand. It has still not been decided what scale will be used in the controllers display. The variation and tendency of the curve are probably more important than the value itself. Nevertheless, it would be necessary to have a reference value that the controllers could identify as complex.

4.3.2 Daily traffic situation

The simulations were also done with a day of typical traffic over REIMS airspace. The traffic comes from a text file of a recorded traffic situation. The Airspace display [4.8] shows the radar image of a controller working position during the first minutes of the simulation.

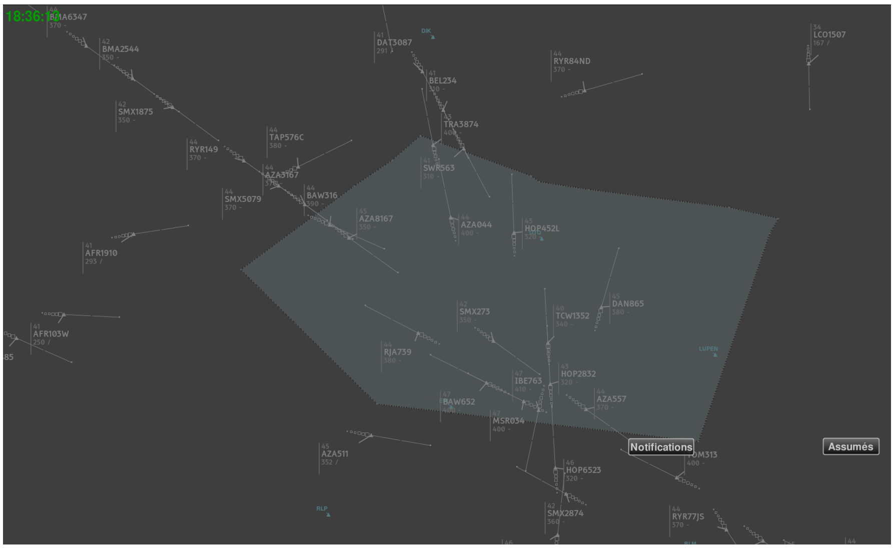


FIGURE 4.8: Air situation display for a daily traffic situation

The results in terms of airspace complexity are shown in the next figure [4.9]. The curve corresponds to the sum of the complexity of every trajectory of the simulation. It is basically a sum of all the pulses from all the conflicts all in one graph. It is not divided in traffic volumes so that the tendency of the whole network can be seen.

The curve shows a peak of complexity in the first minutes of the simulation and then the global tendency is a decrease until null complexity after an hour of simulation. It could look as if there was more complexity at the beginning of the simulation than at the end. Actually, this is not necessarily true. In this case it is because the trajectory predictor only takes into account the flights that are airborne. The airspace complexity computations are only made for those flights, hence, it is normal that the majority of

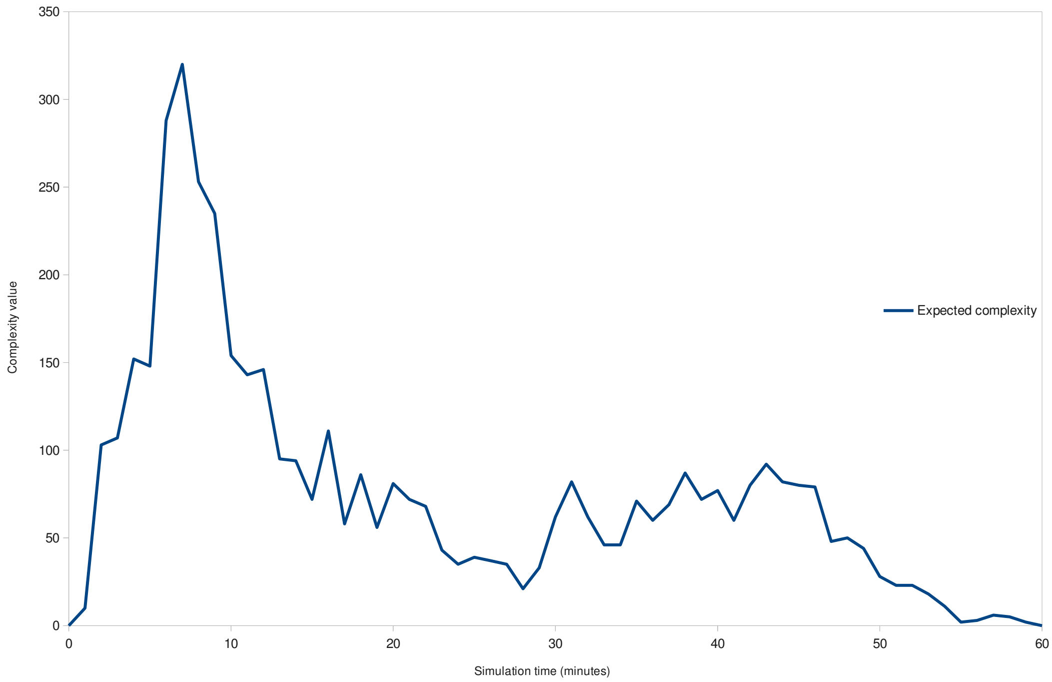


FIGURE 4.9: Complexity curve for a daily traffic situation

flights that will be in REIMS airspace haven't taken off yet. The curve contains peaks because it has a complexity value every minute and hasn't been smoothed.

4.3.3 Airspace complexity HMI

In order to validate the convergence algorithm and the methods implemented in the server, I have developed two curves displays. One that will show the complexity of every selected flight and the other the complexity of every selected traffic volume. The purpose of this basic HMI is simply to debug coding errors and to have a first impression of what the complexity curves look like.

4.3.3.1 Trajectory complexity HMI

This first HMI [4.10] contains a list of the simulated flights. When a flight is selected, it displays its complexity in function of the simulation time (in minutes) as well as the traffic volumes it crosses and the complexity sum, mean and standard deviation of that TV. It was made to validate the methods implemented in the trajectory complexity database. It is useful to know the complexity of some flights in a given traffic volume in order to make a list of the most complex flights. This can give assistance to the EAP when deciding to which flight it is better to apply a regulation. The flight in figure 4.11 is crossing many traffic volumes at the same time because those are subdivisions of bigger traffic volumes. The red line represents the time of the simulation.

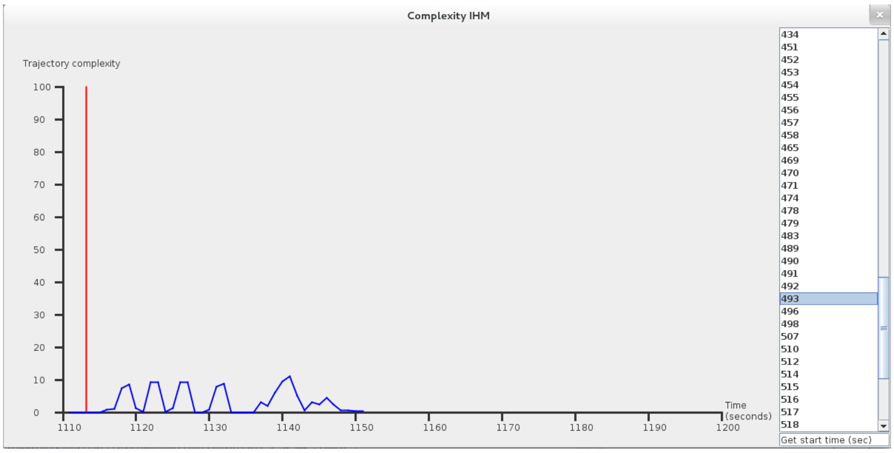


FIGURE 4.10: Complexity of a trajectory in HMI display

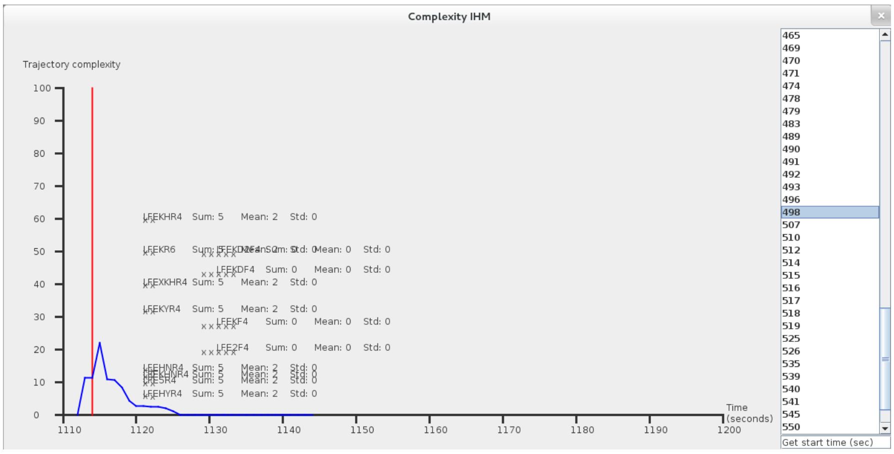


FIGURE 4.11: Complexity of a trajectory in HMI display with TV

4.3.3.2 Traffic volumes complexity HMI

The second HMI is used to validate the traffic volumes complexity computation. There is a list of the traffic volumes of the simulation. When one is selected, it displays its predicted complexity curve during the simulation. It has also two features that are useful implementations of methods. When selecting a point in the curve, the HMI displays the id of the aircraft in the traffic volume and their contribution to the total complexity in that moment. In figure 4.12 it can be seen that at the 1148^{th} minute of the simulation, flights 425, 244 and 243 share the total 45 points of complexity at that minute. All of them almost equally with 31%, 34% and 34% respectively. This information is interesting to understand the part of each of them in complexity.

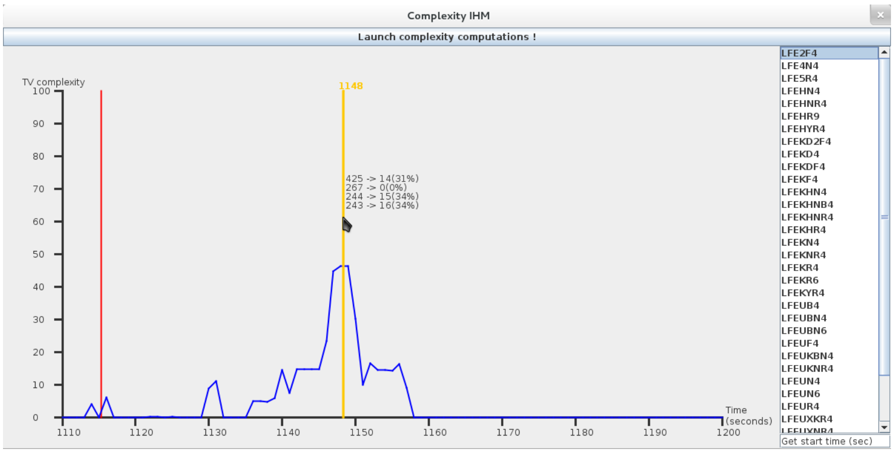


FIGURE 4.12: Complexity of a traffic volume in the HMI display

The second feature of this HMI is the time interval selection. It allows the user to drag and drop with the mouse an interval of the curve to get more information. This feature will also be available for the EAP interface. The information shown is the flights that are in this traffic volume with their complexity sum, mean, standard deviation and their entry and exit time. The complexity data is useful to apply regulations on them. The entry and exit times are used for debug purposes. It is necessary that they are coherent with the one's already computed in the current prototype for the occupancy curves. In figure 4.13 it can be seen that during the time interval that goes from 1144 to 1151 minutes, flights 244 and 243 are the one's with higher complexity. Flight 425 has less total complexity but an equivalent mean value because it spends less time in the traffic volume.

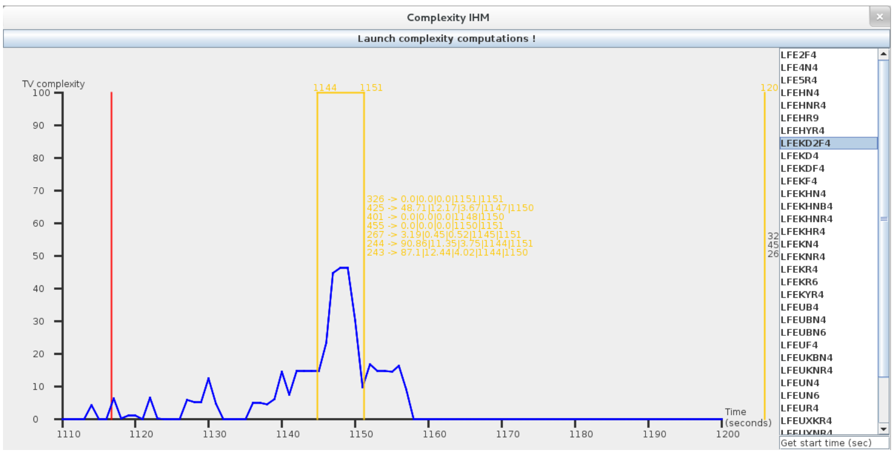


FIGURE 4.13: Complexity of a traffic volume in the HMI display within a time interval

4.4 Future improvements

The algorithm to compute the complexity is still under development. There are issues on the algorithm that need to be improved. Let's see which are the problems and what solutions are proposed to solve them.

4.4.1 Curve precision

A good complexity curve is a curve that predicts complexity with little error. The goal is to obtain the complexity value in the future (up to 2 hours) with the less possible error. This is not an easy task because it depends on many factors.

4.4.1.1 Trajectory prediction uncertainty

First we will be describe the results with only airborne flights. The following simulation has been made with a set of real traffic with 119 flights overflying REIMS airspace. The graphic obtained [4.14] represents the sum of the complexity values of all flights in function of time. The blue curve corresponds to the complexity prediction at the beginning of the simulation, once all trajectories are predicted. The red curve corresponds to the true complexity value obtained in real time.

It can be seen that the blue curve is not exactly the same as the red one because it is based on trajectory prediction. Nevertheless, the error is very small, only caused by the uncertainty of trajectory prediction. The server that computes complexity computes a trajectory for a flight once it has taken off. This prediction is based on the a radar plot, the flight plan, the performances of the aircraft and the standard procedures. It is updated each time the server receives a new radar plot (coordinates where the aircraft really is at that time). Indeed, the prediction cannot be exact because it doesn't take into account all the parameters like the wind or the navigation errors. The trajectory is updated periodically to adjust to the small errors. This is the source of complexity error in this particular case where all flights considered are in the air at the beginning of the run.

This error will not be an important problem because the error is very small and there is not easy solutions to solve it. The trajectory prediction could be improved taking into account the wind but this is not in the scope of the project and there are other greater sources of complexity error.

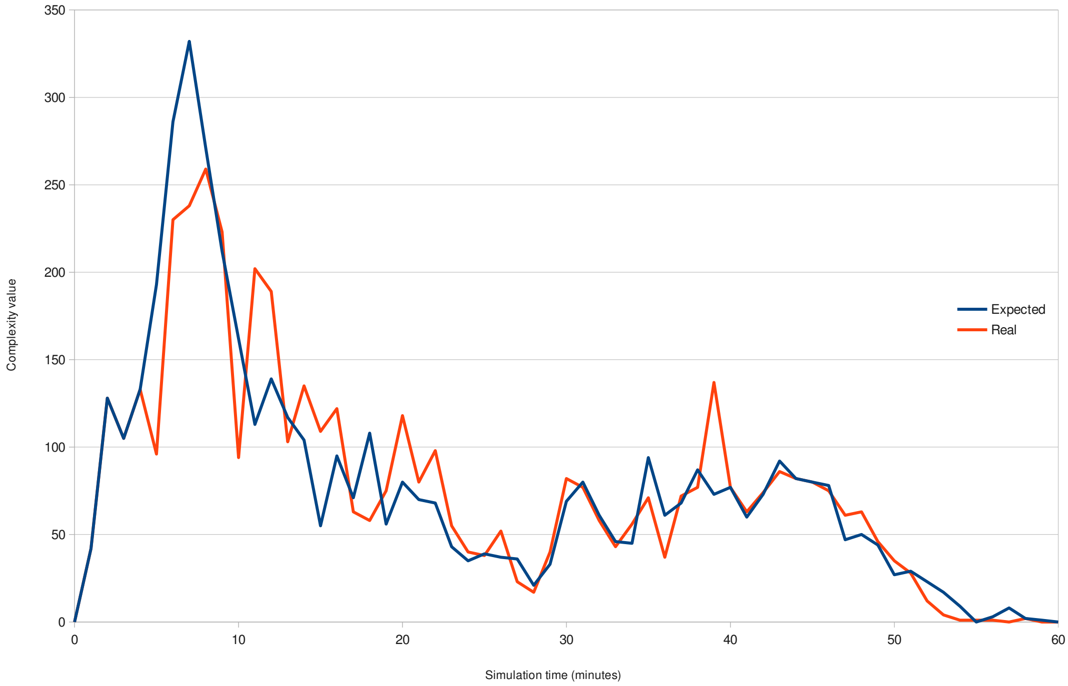


FIGURE 4.14: Complexity prediction curves comparison with error caused by trajectory prediction

4.4.1.2 Take off time uncertainty

Another source of error in the complexity forecast is the take off time uncertainty. This occurs when we want to predict the complexity of flights that haven't took off yet. It will be necessary to do it if we want predictions of 2 hours. For that, the take off time for those flights is taken from the flight plan. This time has to be a multiple of 5 minutes. This means that an airline can set down a flight plan with a departure time of 9h40 or 9h45 for example, but never 9h43. In busy airports like Paris-Charles de Gaulle, there are always several flights with the same departure time but they obviously don't take off at the exact same time. This means that there is an implicit uncertainty in the take off time of every flight that will affect complexity prediction.

In the next graphic I have tried to simulate this uncertainty by applying a positive or negative delay to randomly selected flights in the following proportions:

- -10 minutes to 5% of the flights of the simulation
- -9 minutes to another 5% of the flights of the simulation
- ...

- -1 minute to another 5% of the flights of the simulation and
- 1 minute to another 5% of the flights of the simulation
- 2 minutes to another 5% of the flights of the simulation
- ...
- 10 minutes to another 5% of the flights of the simulation

The set of traffic is the same than before, with 119 real flights overflying REIMS airspace. The results are shown in figure 4.15. The blue curve represents the predicted complexity with the expected departure time (no delays applied). The red curve represents the complexity prediction applying the delays mentioned above.

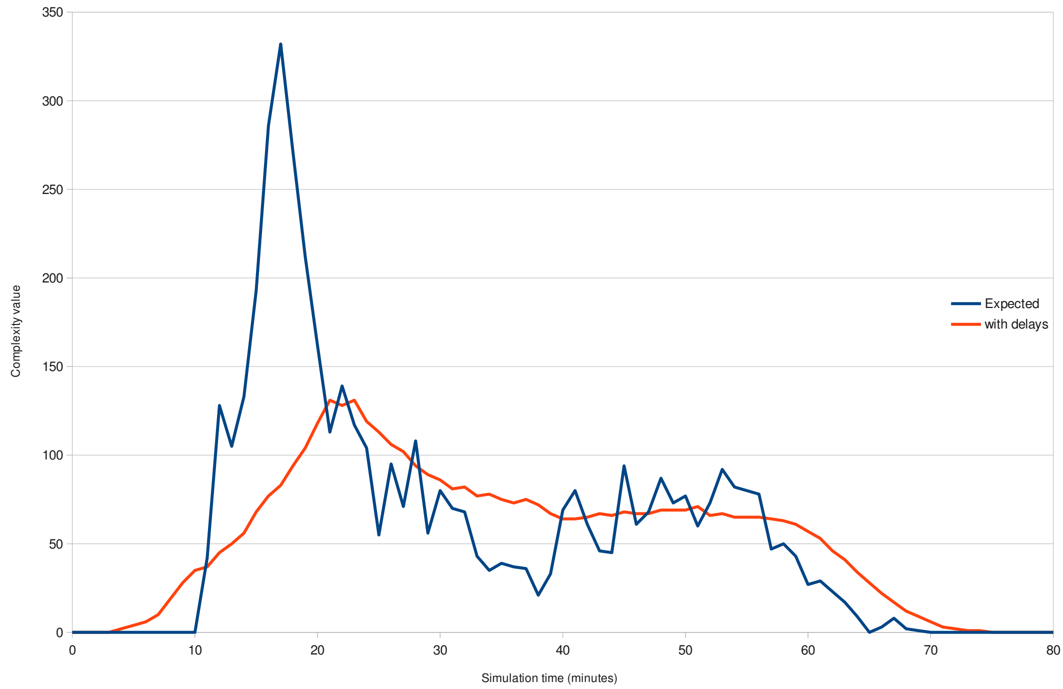


Figure 4.15: Complexity prediction curves comparison with uncertainty caused by departure delay

The prediction with delays is a mean value that has been made in several iterations. It is not just 1 possible scenario but the average of many. This why the curve is smooth and has no picks. It can be seen that the curve is quite similar in the shape except for the complexity pick at 15 minutes. This is quite a problem because the uncertainty curve is very likely to occur. The ATFCM allows a take off time window which varies in function of the situation. When it corresponds to the ETOT (Estimated Take-Off Time), the DTW (Departure Time Window) is ±15 minutes. This is the most common situation as the ETOT is the time set by the flight operator in the flight plan. Another possibility is a STW (Slot Time Window) of −5 minutes to +10 minutes when slot allocation is applied. Eurocontrol decides this take off time which is called Calculated Take-Off Time (CTOT). Whenever flights respect those time windows, it is considered that the flight was on time. According to F. Cioran, Network Manager from EUROCONTROL [13], this happened 88% of the times in 2013. So, 12% the time window is not respected. Hence, the situation previously simulated is very likely to occur. Situations like the ones in figure 4.16, which are obtained with the previous delays, will be constantly happening. It is then absolutely necessary to apply some sort of smoothing to the algorithm in order to obtain a similar curve to the one in figure 4.15 for the prediction. A smoothing solution is proposed at the end of the section.

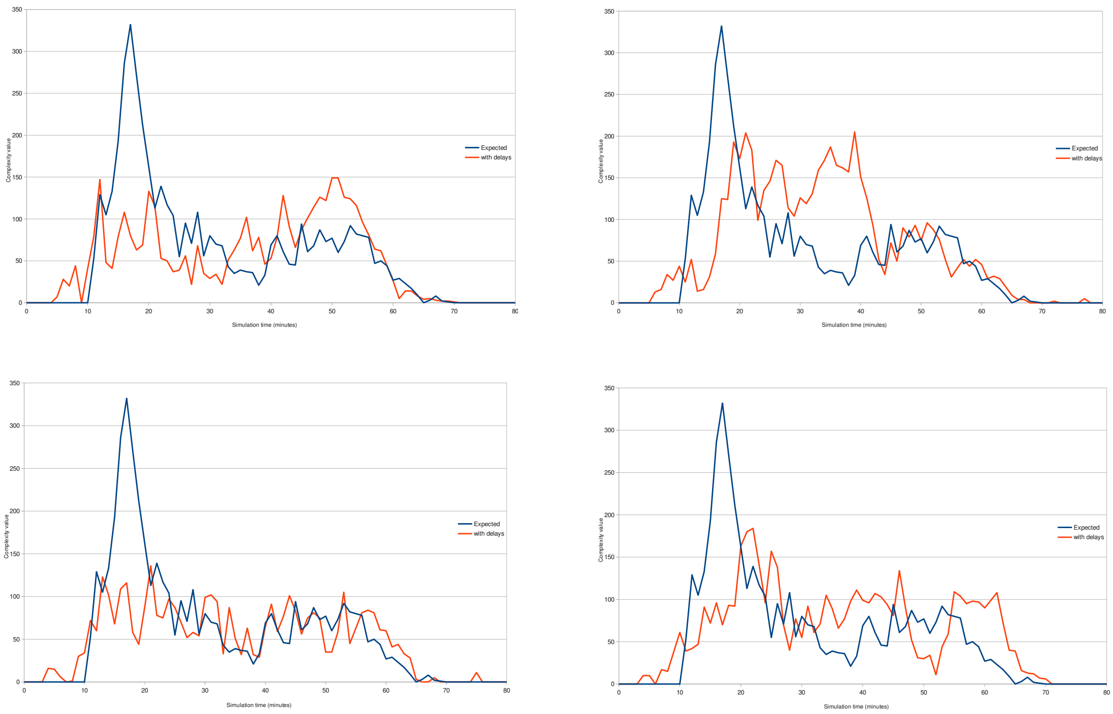


FIGURE 4.16: Possible complexity scenarios applying random delays

To assess the impact of delays in the complexity forecast, another graphic has been drawn. This time the curve tries to quantify the differences between curves. For that, the areas of the curves are compared (the predicted curve and the predicted curve with delays on some flights). 2 curves that doesn't share any area are said to be 100% different. If 2 curves are very different there is a lot of error in prediction. Let's see how much error there is if we apply delay to some flights during a simulation.

In this graph [4.17] there are 3 curves, each of them with their corresponding logarithmic trendline. The X axis corresponds to the amount of delay applied to the flights. The three curves correspond to the percentage of flights on which the delay is applied (10%

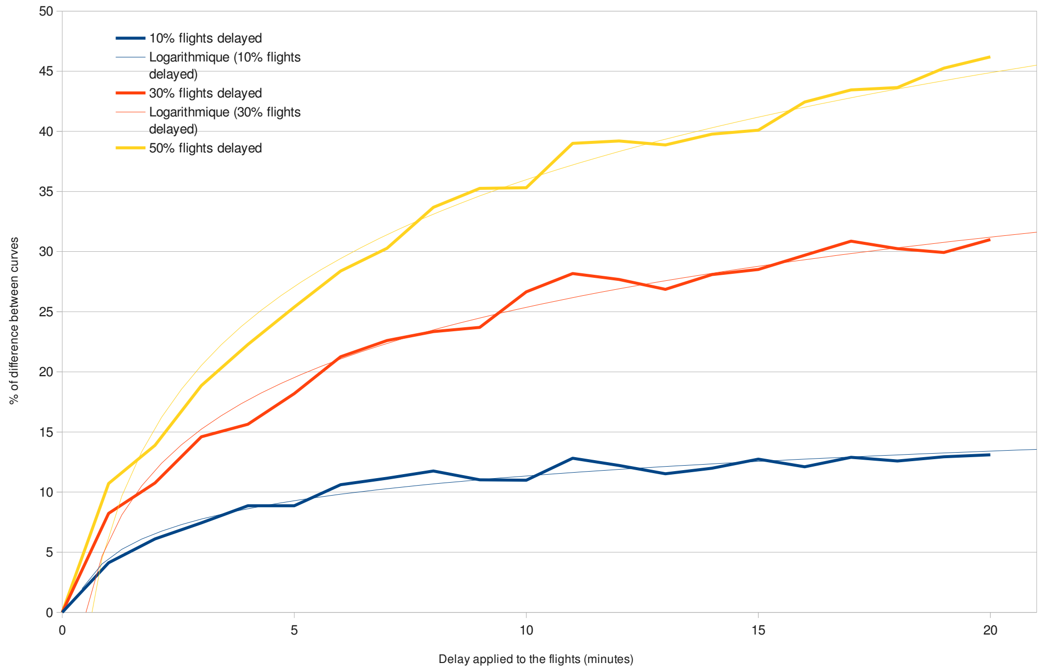


FIGURE 4.17: Complexity error caused by departure delays on some flights

for the blue curve, 30% for the red one and 50% for the yellow one). Finally, the Y axis represents the percentage of difference between the 2 curves, in other words, the error in prediction.

The graphic shows that the more we increase the delay on some flights (X axis), the more prediction error we have (logarithmic tendency). It also shows that for more flights delayed, there is more prediction error too. The yellow curve with 50% of flights delayed has higher values than the blue one with only 10% delayed flights. Those results are coherent, the more the traffic situation is changed, the more the predictions are wrong.

The values are also coherent with the algorithm. Applying 10 minutes of delay to 10% of the flights causes 10% of error between the curves. For 30% of delayed flights there is a 30% error for 17 minutes delay. The curve of 50% delay reaches 45% error at 20 minutes.

An unexpected result is the logarithmic shape of the curves. While increasing the delay, instead of getting more error exponentially or linearly, there is less error increase in high delay values. A logical explanation for this is the conflict duration. An average conflict for the convergence algorithm lasts a maximum of 10 minutes but an average of 5. This means that once a flight is delayed more than 5 to 10 minutes, it will not be in conflict with the same aircraft any more. Thus, the traffic situation has changed creating new conflicts so a new curve. This is why delaying 10 minutes or 20 minutes will not change the error too much because they correspond to new traffic situations. The error is almost constant after 10 minutes delay, especially for a low percentage of delayed flights (blue curve). Different traffic situations have the same average error in prediction.

The prediction curves obtained with 10 minutes delay and those 3 amounts of delayed flights percentages (10%, 30% and 50%) are shown in figure 4.18. It can be seen that the more flights are affected by the delay, the more the curves are switched to the right and are different from the expected one.

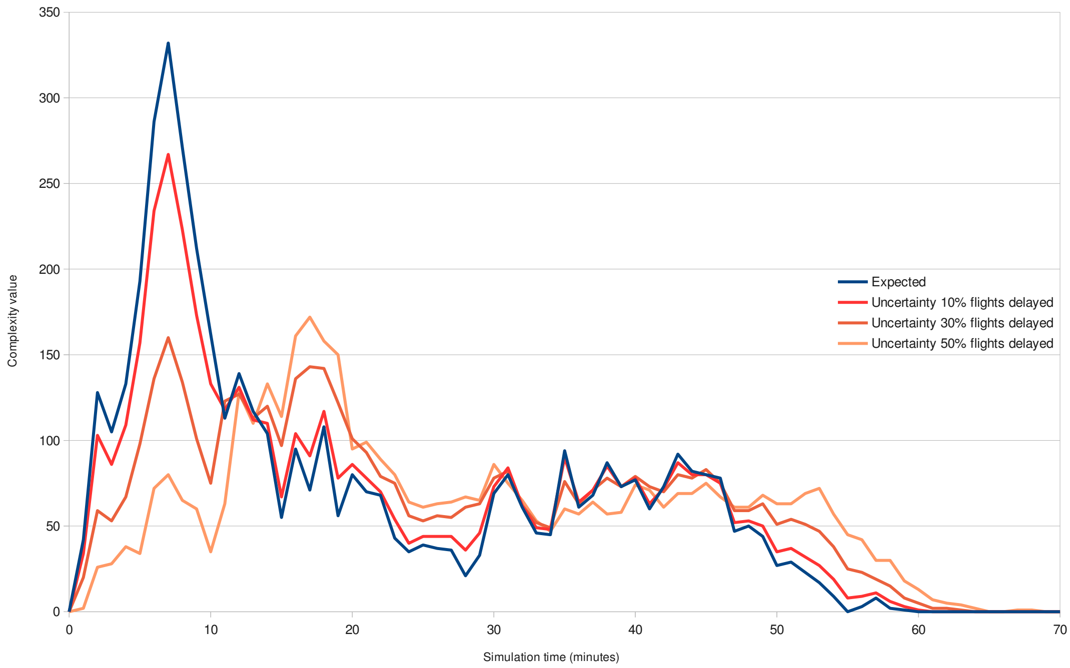


Figure 4.18: Complexity prediction curves comparison with departure delay on some percentage of flights

All those results show that it will be necessary to modify the algorithm in order to have a more stable curve that can smooth the uncertainties, specially when the delay is only for less than 5 minutes, which happens in regular basis. A solution considered is to modify the way that the algorithm computes the convergence with respect to other flights. To compute the complexity of a flight, the algorithm uses the position and speed vector of the other surrounding aircraft in that same time. The idea is that, instead of considering only the position of the aircraft at the same time, it could be also computed as the mean value of several planned positions of the aircraft some minutes after and some minutes before. This way we could simulate a possible delay or anticipation of the flight to have a more average and stable value. This method is detailed later in figure 4.20.

4.4.1.3 On ground flights

The biggest source of error are aircraft that are still on ground. They are not considered in the complexity curve because they still don't have a trajectory prediction. The trajectory predictor (TP BADA) only takes into account airborne flights. This causes the curve to have a huge instability because flights only appear in the curve when they take off. This doesn't allow to make a 2 hours forecast. It can be seen in figure 4.19 that the real complexity curve doesn't correspond at all with the predicted one. Indeed, the predicted one only considers airborne flights. The curves are similar at the beginning because the flights considered are already flying. One hour later, the majority of flights are still on ground so they are not considered in the blue curve, that has obviously very little complexity value.

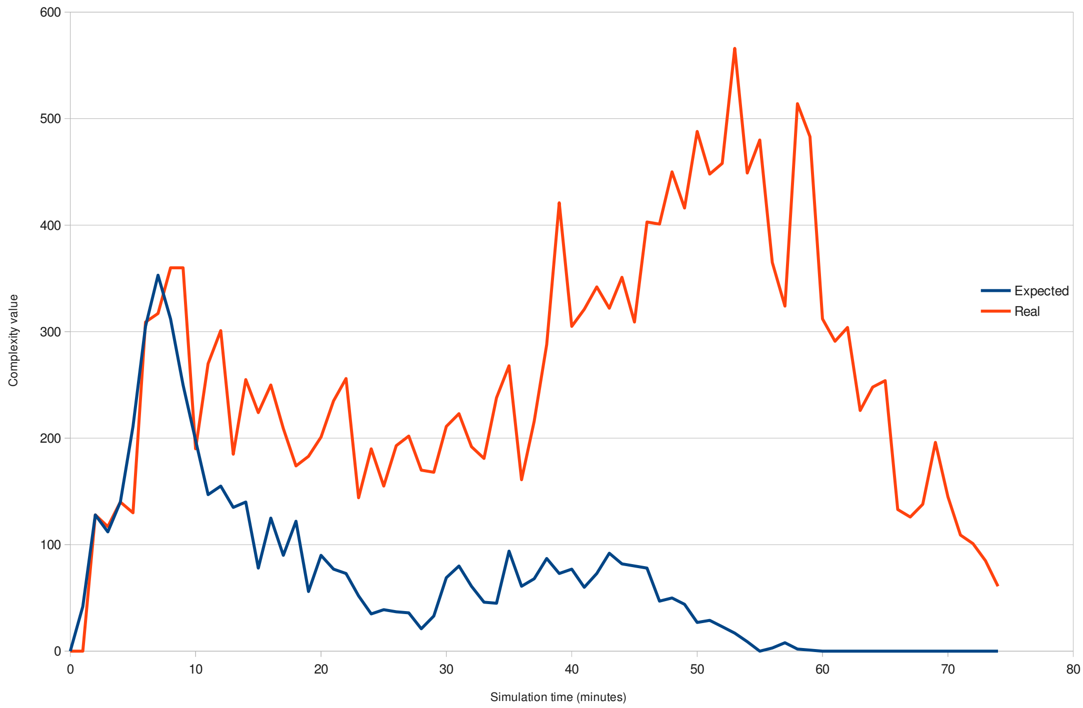


FIGURE 4.19: Real complexity compared to prediction (airborne flights only)

The trajectory predictor (TP BADA) will have to be modified to take into account also flights that haven't took off yet in order to have a trajectory prediction for them too. However, we have seen that the take off time provided in the flight plan is not very accurate and certain. Their take off time is really uncertain. This is why it is necessary to find a solution to distinguish airborne flights from on ground flights.

A possible solution [4.20], not yet implemented, would be to use a bigger time window when computing the convergence of uncertain flights. As explained before, instead of using a single plot to compute complexity, it would be better to use several expected positions of the flight and then take an average value of them. The more uncertain the flight is, the more points should be considered in the complexity computation. As for the display, there are not solutions decided to represent this difference between on ground and airborne flights. Figure 4.20 shows the computation of complexity with this method. Currently, the algorithm only considers the value where the two aircraft (AC1 and AC2) are expected to be (cx3) at the same time. It is planned to also take into account the positions where the second aircraft will be some time before and after. The flight is very likely to be in one of those positions if the flight is delayed.

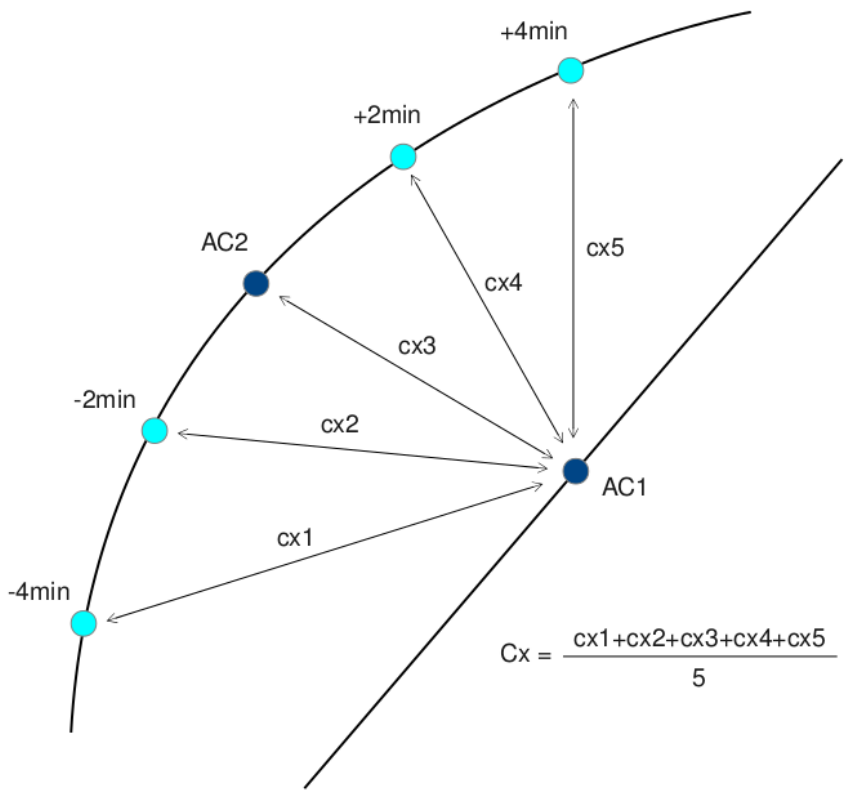


FIGURE 4.20: Computation method to improve the algorithm stability

The size of the time window and the weighting of complexity points will need to be decided.

4.5 Difficulties

In this final section will be discussed the challenges faced during the performance of the internship and what solutions where applied to overcome them.

4.5.1 Lack of airspace complexity background

As mentioned through the report, the airspace complexity is a relatively new concept. Although there has been research on the subject for 20 years, there is a clear lack of operational background on the subject, specially in France, where this metric has never been implemented in a control center. Furthermore, there is not a clear definition of what it is because every proposed algorithm computes it in a different way. The fact that airspace complexity has no unit shows how the meaning of complexity changes from algorithm to algorithm.

Those facts have been important when taking decisions on the server features. For example, the choice of a scale for the HMI. First, the choice of an appropriate magnitude. Whereas to put a value of 10, 100 or 1000 for a small value of complexity (easy traffic situation). Then, how to define a maximum. A priori, there is not a maximum convergence value but one could be defined, for example in an unsustainable situation for a controller. But again, this remains subjective for every controller and needs operational background to be defined. This issue will have to be defined after some simulations with controllers that will give background on the situation.

4.5.2 Availability of the complexity algorithms

The complexity algorithm used in the server (”convergence”) was not available until the second part of the internship due to the unavailability of the ENAC researchers. This forced me to do the whole server before having any complexity data. This added difficulty to the tests with complexity data during the second part of the internship.

4.5.3 Lack of specifications for the complexity server

The complexity server had not been initiated yet so all the code had to be done. The specifications came from two sides. First, the HMI for the EAP was planned to have 2 complexity values: the curves per traffic volume and the complexity per flight. Those were the only two outputs intended for the server. But none of it stated what mathematical operation apply to obtain them. Then, there was also intended data for the trace files of the server: complexity divided in traffic volumes and in flights, all for a 2 hours forecast. Apart from that, there were no specifications on the structure of the server like class diagrams or required inputs.

This forced me to, first, understand the specific code language of the prototype (communication protocols, class types, bus architecture. . .) and then take examples from other servers to make my own one. This lack of specification was positive also because it gave me freedom to apply my own ideas and think by myself how to make it work. I felt that this way of working was flexible and efficient.

Conclusion

During this internship at Sopra-Steria I have developed and integrated an airspace complexity server in the existing EAP prototype. This prototype is part of the SESAR P478 that seeks to define and validate the need of a new actor in the en-route control room, the Extended ATC Planner. The software product I have developed is in charge of computing and providing airspace complexity information to this new role to help him performing his duty.

The complexity server consists on getting flight trajectories, computing an airspace complexity value for them using an algorithm and finally sending this information divided in Traffic Volumes to the EAP display. It can also store trace data during a simulation to obtain useful graphics for validation purposes. The server also integrates an HMI developed for validation and testing purposes. Finally, it includes methods to assess prediction errors in complexity curves.

The basis of the airspace complexity for the EAP are set. The perspectives of the project are to improve the existing code to make it more useful for the controllers and adapted to reality. At some point, operational feedback will be needed. The fact that airspace complexity is a very new concept in French en-route control centers, makes that many factors are still undefined or not proved. Live trials will help to assess those factors such as the scale of the complexity, the quantification in terms of complexity of a complex/difficult situation or the complementarity with the occupancy curves. After trials it would be necessary to assess the precision of the complexity forecast by the analysis of the trace files after a real day of operations (this post analysis of the data was done during the internship). Another not really validated assumption is that applying a STAM to the flight with the highest complexity value is always the best option to alleviate complexity in a traffic volume. Another uncertainty is the mathematical operation to be applied to the complexity values when computing traffic volume complexity and flights complexity. At the moment, the values displayed are always the sum but the code written on the server is able to give also a mean value and a standard deviation value. Those can also be displayed as complementary values to give more information to the controller. As for the complexity algorithms, the Convergence has still room for improvement like including conflict distance in the computation. The take-off uncertainty remains an important issue too. It has been proved that airspace complexity prediction is very vulnerable of take-off uncertainty. The proposed solution is to compute a mean of several points of the trajectory to have an average value of complexity. The curve would greatly improve in smoothness and stability. Later on, it would also be interesting to integrate the second complexity algorithm, the Lyapunov exponents algorithm. This would allow to compare the two kinds of complexity values and assess which one represents better the feeling of complexity for an air traffic controller.

Glossary

ANSP	**A**ir **N**avigation **S**ervice **P**rovider
APW	**A**rea **P**roximity **W**arning
ASD	**A**ir**S**ituation **D**isplay
ASM	**A**ir**S**pace **M**anagement Processes
ATC	**A**ir **T**raffic **C**ontrol
ATM	**A**ir **T**raffic **M**anagement
ATFCM	**A**ir **T**raffic **F**low and **C**apacity **M**anagement
CDM	**C**ollaborative **D**ecision **M**aking
CENA	**C**entre d'**E**tude de la **N**avigation **A**érienne
CFMU	**C**entral **F**low **M**anagement **U**nit
CHMI	**C**FMU **H**uman **M**achine **I**nterface
CNS	**C**ommunication **N**avigation and **S**urveillance
CRNA	**C**entre en-**R**oute de la **N**avigation **A**érienne
CTOT	**C**alculated **T**ake-**O**ff **T**ime
CWP	**C**ontrol **W**orking **P**osition
dDCB	dynamic **D**emand **C**apacity **M**anagement
DGAC	**D**irection **G**énérale de l'**A**viation **C**ivile
DSNA	**D**irection des **S**ervices de la **N**avigation **A**érienne
DTI	**D**irection de la **T**echnique et de l'**I**nnovation
DTW	**D**eparture **T**ime **W**indow
ETMS	**E**nhanced **T**raffic **M**anagement **S**ystem
ETOT	**E**stimated **T**ake-**O**ff **T**ime
ENAC	**E**cole **N**ationale de l'**A**viation **C**ivile
FAB	**F**unctional **A**irspace **B**lock
FM	**F**low **M**anager

FMP	**F**low **M**anagement **P**osition
HMI	**H**uman **M**achine **I**interface
IT	**I**nformation **T**echnology
LTM	**L**ocal **T**raffic of **M**anager
MDI	**M**inimum **D**eparture **I**nterval
MIT	**M**assachusetts **I**nstitute of **T**echnology
MSP	**M**ulti **S**ector **P**lanner
NM	**N**etwork **M**anager
NMOC	**N**etwork **M**anagement **O**peration **C**enter
PC	**P**lanner **C**ontroller
RBT	**R**eference **B**usiness **T**rajectory
SBR	**S**u**B**-**R**egional Manager
SESAR	**S**ingle **E**uropean **S**ky **A**TM **R**esearch
SESAR JU	**S**ingle **E**uropean **S**ky **A**TM **R**esearch **J**oint **U**ndertaking
STAM	**S**hort-**T**erm **A**TFCM **M**easure
STCA	**S**hort-**T**erm **C**onflict **A**lert
STW	**S**lot **T**ime **W**indow
TC	**T**actical **C**ontroller
TONA	**T**ake **O**ff **N**ot **A**fter
TONB	**T**ake **O**ff **N**ot **B**efore
TP	**T**rajectory **P**redictor
vDFL	**v**ariable **D**ivision **F**light **L**evel
WP	**W**ork **P**ackage

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